International Journal of Chemical Science and Research

www.ijcsrjournal.com

Volume - 01
Issue - 02
Month - July
Year - 2026

MODERN ANALYTICAL TECHNIQUES FOR CHEMICAL CHARACTERIZATION OF ENVIRONMENTAL AND PHARMACEUTICAL SAMPLES: A STATE-OF-THE-ART REVIEW

Mohammad Nofil

Low Dimensional Materials Research Centre (LDMRC), Department of Physics, Faculty of Science, University Malaya, 50603, Kuala Lumpur, Malaysia

Received:- 12/06/2026 , Revised:- 13/07/2026 , Accepted:- 20/07/2026 , Published:- 27/07/2026

ABSTRACT

The reliable characterisation of environmental and pharmaceutical samples containing chemically diverse substances at trace and ultra-trace levels requires the use of modern analytical techniques. This review covers the main methods for sampling, sample preparation, separation, detection, characterisation, and data processing of contaminants, active pharmaceutical ingredients, impurities, degradation products, metabolites, toxic elements, microplastics and emerging pollutants. Complex mixtures can be effectively resolved using chromatographic methods such as HPLC, UHPLC, gas chromatography, hydrophilic interaction chromatography, multidimensional separations, and supercritical fluid chromatography. They can be coupled with tandem and high-resolution mass spectrometry to enable targeted, suspect screening, non-target and structural elucidation. The UV-visible, fluorescence, FTIR, NIR, Raman, SERS, NMR, ICP-MS, AAS, DSC, TGA, SEM, TEM, XRD, XPS and AFM techniques provide a range of information on molecular and structural composition and characterisation, elemental, thermal, morphological and surface characterisation, respectively. Portable and on-site analysis is improved with electrochemical sensors, biosensors and miniaturised systems. Other interesting topics presented in the review include matrix effects, sample stability, validation needs for analytical methods, chemometric modelling, machine learning, green analytical chemistry and regulatory aspects. Further developments are likely to be directed towards automation, portability, AI, digital twins, real-time monitoring and harmonised analytical standards to achieve more sustainable, sensitive and reliable chemical analysis.

KEYWORDS

Environmental analysis; Pharmaceutical characterisation; Mass spectrometry; Spectroscopic techniques; Green analytical chemistry

1. INTRODUCTION

Characterisation of chemicals is fundamental for environmental surveillance, drug development, regulatory affairs, quality control and safety to the population. Chemically diverse materials can exist in a sample, either as major components or in ultra-trace amounts, in environmental or pharmaceutical samples. These substances include pharmaceuticals, pharmaceutical contaminants, metabolites, degradation products, pesticides, personal care products, toxic elements, microplastics, and other emerging contaminants. They have to be accurately identified and quantified in many cases to determine the quality of the samples, chemical stability, biological exposure, contamination in environment and potential risk to the ecosystems and human health.

Pharmaceuticals can be found in wastewater, surface water, groundwater, soil, sediment and biological organisms. They are linked to the presence in the environment due to widespread use of pharmaceuticals, inadequate metabolism, domestic and industrial discharges, faulty disposal methods, use in agriculture and lack of removal during typical wastewater treatment. Pharmaceutical residues are distributed all over the world, indicating the need for sensitive analytical monitoring of these residues to identify their sources, persistence, distribution and ecological effects (Aus der Beek et al., 2016). Besides traditional end-of-pipe approaches, preventive measures are needed to achieve effective control of pharmaceutical residues and aquatic micropollutants. Pharmaceuticals can be released during the manufacturing process, use, human excretion, disposal, during treatment of wastewater, and by transformation in the environment. Therefore, initial measures for input prevention and integrated measures for emission management need to be emphasised more along the chemical products' life cycle (Kümmerer et al., 2019).

There is a large number and variety of emerging contaminants, which pose significant analytical challenges in the routine environmental analysis. Most contaminants, metabolites, reaction by-products and transformation products are not regulated and are either not well characterised or not included in regular monitoring programmes. Modern water analysis, therefore, needs to be capable of identifying known, unknown and unexpected contaminants as well as high sensitivity, selectivity, accuracy and structural information (Richardson & Kimura, 2019). Pharmaceutical pollution occurs across the geographical spectrum as well. Pharmaceutical residues were found in many parts of the world, and the concentrations found in rivers were shown to potentially impact the health of aquatic organisms and ecosystems during a global investigation of rivers (Wilkinson et al., 2022). This worldwide event underscores the importance of standardisation, replicability and international applicability of the analytical procedures for environmental surveillance and risk assessment.

Environmental samples present a challenge to chemical analysis because of the changing composition of the matrix, the concentration of the analytes, changes in the physicochemical behaviour or the presence of interference. Each type of water, wastewater, soil, sediment and sludge, and biological tissue needs different extraction, cleanup, separation and detection processes. Therefore, it is necessary to consider and optimise all the steps of the analytical procedure to isolate the pharmaceutical and personal-care products in solid and liquid environmental samples (Alqarni, 2024).

Many complex mixtures are separated before qualitative and quantitative analysis by chromatographic methods, making these crucial. The resolution, sensitivity, automation, and reproducibility of HPLC have been enhanced, and the technique is increasingly used in drug analysis, impurity profiling, biological research, and monitoring of contaminants in the environment (Singh et al., 2025). Spectroscopic techniques are often used to complement other analytical techniques and can often allow for rapid, non-destructive and minimally destructive analysis. The advantages of NIR include minimal sample preparation and high throughput for pharmaceutical quality control (PQC), making it a particularly useful tool for raw material identification, quantitative analysis, process monitoring, formulation evaluation and chemometric classification (Ozaki et al., 2021).

Another large challenge in analysis is the presence of microplastics. Microplastic particles can be of different sizes, shapes, chemical makeup, surface characteristics and contaminants. Generally, they are characterized using a combination of microscopy, vibrational spectroscopy, thermal analysis and mass spectrometry to identify the polymer and its environmental behaviour, which is reliable (Bhatt et al., 2021). Along with the product characterisation, the characterisation of impurities is also crucial in pharmaceutical analysis as impurities may impact the safety, efficacy, stability and regulatory acceptability of the product. These can be: starting materials, intermediates, process by-products, residual solvents, degradation products, elemental impurities and packaging-related contaminants. Advanced techniques are, therefore, needed to detect known and unknown impurities in Active Pharmaceutical Ingredients and Finished Pharmaceutical products (Finotti Cordeiro et al., 2026).

The performance of the analysis should be sustainable. The conventional processes can use potentially

dangerous solvents, reagents, energy, and disposable materials, and generate contaminated waste. Green analytical chemistry metrics offer systematic means of assessing the utilisation of solvents, waste production, energy use, operational risks and environmental footprint (Sajid and Płotka-Wasylka, 2022).

Therefore, this review critically analyses the analytical methods (chromatographic, mass-spectrometric, spectroscopic, elemental, electrochemical, sensor-based and miniaturised) for environmental and pharmaceutical characterisation. It reviews their principles, requirements for sample preparation, applications, advantages, limitations, validation considerations, sustainability and provides insights on advances in high resolution analysis, portable instrumentation, automation, chemometrics, artificial intelligence, green analytical chemistry, research gaps and future directions.

2. ENVIRONMENTAL AND PHARMACEUTICAL SAMPLES: TYPES AND ANALYTICAL CHALLENGES

Environmental and pharmaceutical analysis deals with a vast array of samples which can vary greatly in composition, complexity, stability and analyte concentration. Environmental samples include surface water, wastewater, drinking water, ground water, plants, aquatic life, air particulates, sludge, soil and sediment. Typical samples for the pharmaceutical industry are active pharmaceutical ingredients, excipients, intermediates, raw materials, capsules, tablets, single-dose products, and biological fluids, such as blood or plasma, and packaging extracts and degradation products. The analytical needs for each sample type are unique, and the compounds of interest can be found at trace or ultra-trace levels within chemically complex matrices. Table 1 provides an overview of the types of environmental and pharmaceutical samples, typical analytes in each sample type, analytical problems encountered in these samples and recommended analytical methods.

Table 1. Major Environmental and Pharmaceutical Sample Types and Their Analytical Challenges

Sample category	Representative samples	Common target analytes	Major analytical challenges	Suitable analytical approaches
Water samples	Surface water, groundwater, wastewater, drinking water	Pharmaceuticals, pesticides, personal-care products, metals	Trace concentrations, dissolved organic matter, variable pH	SPE–LC-MS/MS, GC-MS, ICP-MS
Solid environmental samples	Soil, sediment, sludge	Persistent pollutants, metals, microplastics	Strong analyte binding, heterogeneous composition	Solvent extraction, XRD, FTIR, ICP-MS
Biological environmental samples	Fish, plants, tissues	Metabolites, bioaccumulated contaminants	Proteins, lipids, endogenous compounds	QuEChERS, LC-HRMS, GC-MS
Pharmaceutical raw materials	APIs, excipients, intermediates	Active ingredients, impurities, residual solvents	High analyte concentration, structurally related impurities	HPLC, GC-MS, FTIR, NMR
Finished pharmaceutical products	Tablets, capsules, injectables	APIs, degradation products, excipients	Matrix interference, content-uniformity requirements	UHPLC, Raman, NIR, LC-MS
Biological pharmaceutical samples	Plasma, serum, urine	Drugs and metabolites	Ion suppression, protein binding, low concentration	Protein precipitation, SPE, LC-MS/MS

Environmental samples are often complex matrices which may contain a variety of organic and inorganic compounds that may interfere with the extraction, separation, ionisation, and detection of analytes. Analytical responses from the target compounds can be like and/or may be masked by dissolved organic matter, salts, suspended particles, lipids, proteins, pigments or naturally occurring chemicals. In LC tandem mass spectrometry, co-eluting matrix components can inhibit or facilitate analyte ionisation, which can impact the quantitative accuracy (Gosetti et al., 2010).

Water samples are typically less complex than soil, sediment or sludge or biological tissue, but contaminants found in water are typically at very small levels. They may therefore need to be sampled in large volumes, enriched, selectively extracted, and be highly sensitive to detect them. Solid environmental matrices, however, are those that have strongly bound contaminants, which can affect the organic matter, minerals, or particulate surfaces. Solvent selection, agitation, sonication, pressurised extraction and other pretreatment processes are necessary to efficiently extract from such matrices.

Pharmaceutical materials are also highly complex to analyse. Excipients are components of finished formulations that include fillers, binders and coatings, preservatives, colourants and stabilisers. These components can be interfering or degradation products. Biological samples requiring pharmacokinetics, toxicological or biomonitoring studies are even more difficult as proteins, phospholipids, salts and endogenous metabolites can affect sample recovery and instrumental response. Therefore, if not properly evaluated and minimised, these biological matrix effects may lead to inaccurate measurement of analytes, unacceptable method precision and poor calibration (Panuwet et al., 2016).

A large physicochemical variation of the targets is another problem. The polarity, molecular mass, volatility, solubility, ionisation characteristics, thermal stability and chemical reactivity of environmental and pharmaceutical compounds can vary. One analytical technique might thus not be able to extract and quantify all the compounds of interest with the same efficiency. Multiresidue and multiclass methods demand thoughtful optimisation to ensure recovery of the analytes, chromatographic separation and detector response of a diverse group of analytes.

A major disadvantage of LC–MS is matrix effects, which occur when multiple compounds are introduced into the ion source at the same time, thus competing during the droplet formation and evaporation and during the ionisation process. This phenomenon can cause a reduction or increase in the intensity of the signal, depending on the composition of the sample and the conditions of ionisation. Such methods as matrix-matched calibration, the use of stable-isotope labelled internal standards, sample dilution, better chromatographic separation and more selective purification techniques (Cappiello et al., 2010) can be used.

Sample stability is another important factor to consider. During the collection, transportation, storage, and preparation of pharmaceutical compounds and environmental contaminants could undergo hydrolysis, oxidation, photolysis, microbial degradation, or be adsorbed to the surface. The original chemical composition of the sample, therefore, may be altered before it is analysed if it is handled inappropriately. The preservation conditions, the storage temperature, the material of the container, the storage period and the protection from light should be determined according to the properties of the compound to be preserved.

Therefore, it is necessary to specify the analytical procedure for the sample matrix and the purpose of the investigation to obtain a reliable characterisation. To reduce uncertainty, representative sampling, effective extraction, adequate cleanup, selective separation, sensitive detection and rigorous quality control. Therefore, an understanding of the composition of the matrix and the behaviour of the analytes is critical for the design of the method to give accurate, precise, reproducible and scientifically defensible results.

3. SAMPLING AND SAMPLE-PREPARATION TECHNIQUES

In the chemical characterisation of environmental and pharmaceutical samples, sampling and sample preparation are very important steps since the reliability of the instrumental analysis relies on the representativeness, stability and cleanliness of the material introduced in the analytical system. Even with advanced instruments, errors can happen in the collection, preservation, extraction, and clean-up of samples, which can lead to inaccurate results. The analytical procedure, therefore, should be designed to start with a sampling strategy appropriate for the type of matrix, the expected concentration of the analyte, and the purpose of the investigation. The sequential workflow from representative sampling to sample preparation, instrumental analysis, validation and final interpretation is displayed in Figure 1.

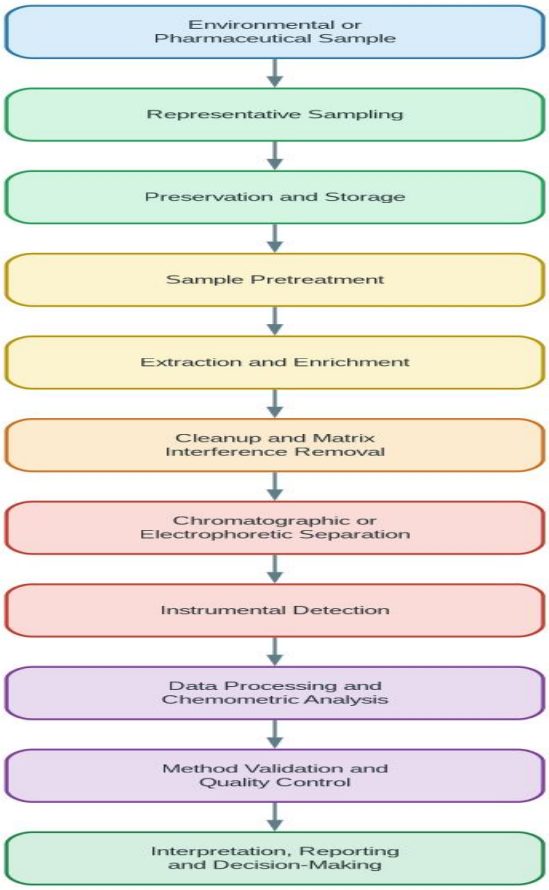

Figure 1. General workflow for the chemical characterisation of environmental and pharmaceutical samples

Environmental samples can range from water and wastewater to plants, biological organisms, air particulates, soil, and sediment, as well as sludge. There exists an appropriate protocol for the sampling of each matrix that will reduce contamination, analyte loss and chemical transformation. Water can be taken in grab or composite samples, depending on whether they are short-term variations or average contamination being measured. Representative subsampling needs to be performed for solid matrices if the pollutant is not homogeneously distributed. Similarly, for pharmaceutical sampling, raw materials, intermediates, finished products, and stability samples need to be carefully selected to represent the entire batch for analysis.

When analytes are unstable or likely to oxidise, hydrolyse, photolyse, volatilise, be degraded by microbes or adhere to the walls of the container, sample preservation is necessary. Cold storage, freezing, pH adjustment, filtration, preservative or light protection may be required, depending on the properties of the analytes. Furthermore, storage time should be kept as short as possible to avoid changes in the concentration and/or chemical form of the analyte.

Extraction: Separation and concentration of target compounds before further analysis by chromatography, spectroscopy or mass spectrometry. A well-established liquid–liquid extraction technique can be used for many organic contaminants, but usually requires large amounts of toxic solvents. The dispersive liquid–liquid microextraction technique has several advantages, such as high sample enrichment, low solvent consumption, and relatively simple operation, especially in pesticide analysis, which are key features of the technique (Ahmad et al., 2015). Single-drop and hollow-fibre techniques are among other types of liquid-phase microextraction. These techniques minimise solvent consumption and waste, and are found to be efficient in extraction, with the efficiency depending on the solvents used, pH, ionic strength, agitation, extraction time, and the polarity of the analytes (Hashemi et al., 2017).

The concentration and removal of analytes and matrix interferences from environmental waters and pharmaceutical formulations are commonly performed by solid-phase extraction. The kind of sorbent used is influenced by the charge, chemical functionality, molecular size and polarity of the analyte. QuEChERS is a combination of solvent extraction, salt-assisted partitioning and dispersive cleanup, which is rapid, versatile, cost-effective and applicable to multiresidue analysis by gas or liquid chromatography.

Dispersive solid phase extraction is routinely used after extraction to clean up pigments, lipids, organic acids,

water and other matrix elements. In comparison to traditional materials, such as activated carbon, advanced sorbents, like nanomaterials, magnetic particles, molecularly imprinted polymers and modified carbon materials, offer larger surface area, rapid equilibration time, and increased interaction between the analyte and sorbent (Ścigalski & Kosobucki, 2020). The main sample preparation techniques, their principles, applications, advantages and limitations are compared in Table 2.

Table 2. Comparison of Major Sampling and Sample-Preparation Techniques

Technique	Basic principle	Main advantages	Main limitations	Typical applications
Liquid–liquid extraction	Partitioning between immiscible solvents	Simple and widely applicable	High solvent consumption, emulsion formation	Organic contaminants and pharmaceuticals
Dispersive liquid–liquid microextraction	Fine dispersion of extraction solvent	High enrichment and low solvent use	Sensitive to solvent and pH selection	Pesticides and trace pollutants
Solid-phase extraction	Retention on a selective sorbent	Effective cleanup and concentration	Sorbent cost and possible analyte loss	Water contaminants and pharmaceutical preparations
Solid-phase microextraction	Sorption onto a coated fibre	Solvent-free and automatable	Limited capacity and coating fragility	Volatile and semi-volatile compounds
QuEChERS	Salt-assisted extraction and dispersive cleanup	Fast, economical, and adaptable	May require matrix-specific modification	Multiresidue analysis
Ultrasonic-assisted extraction	Acoustic disruption of sample matrix	Rapid and relatively simple	Possible analyte degradation	Soil, sediment, plants, and pharmaceuticals
Microwave-assisted extraction	Microwave-induced heating	High extraction efficiency	Requires specialised equipment	Solid environmental matrices
Pressurised liquid extraction	Solvent extraction at high pressure and temperature	Rapid and automated	High instrument cost	Soil, sediment, and polymer samples

Other sample-preparation techniques include solid-phase microextraction, ultrasonic-assisted extraction, microwave-assisted extraction, pressurised liquid extraction, supercritical-fluid extraction and membrane-based separation. These techniques are chosen based on the physicochemical properties of the analyte and matrix. This modern sample preparation has put a high priority on automation, miniaturisation, low solvent usage, quick extraction time and direct connection to sophisticated analytical instruments.

An ideal sample preparation procedure should recover high amounts of the analyte, reduce the interference from the matrix, be reproducible, be sufficiently sensitive, and limit the use of costly, time-intensive solvents and waste. Optimisation and validation of the methodology should then be warranted to ensure that the chosen sampling and preparation method is suitable for the intended environmental or pharmaceutical application.

4. CHROMATOGRAPHIC AND SEPARATION TECHNIQUES

Chromatography and separation techniques play a crucial role in the chemical characterisation of environmental and pharmaceutical samples, as they help to separate complex mixtures into their individual components, allowing them to be identified and quantified. They play a special role in the presence of structurally related compounds, degradation products, metabolites, excipients, natural organic matter, and other components of the matrix. The choice of method depends on the polarity, volatility, size, thermal stability, ionisation properties of the analyte, complexity of the matrix and desired analytical sensitivity.

Liquid chromatography is commonly used for non-volatile, polar, thermally labile and high molecular weight compounds which cannot be chromatographed using gas chromatography. The resolution, analysis time, solvent use and detector compatibility of high-performance liquid chromatography and ultra-high-performance liquid chromatography are better than for conventional HPLC. The analytical column is not the only component that affects chromatographic performance; there are also "extra-column" components such as tubing, injectors, and detector cells. Band broadening and peak overlap may compromise efficiency, so care should be taken to ensure that connection tubing, injection volume, detector-cell volume, and instrument configuration will not compromise resolution and sensitivity (Desmet & Broeckhoven, 2019).

Moderately polar compounds like pharmaceuticals, pesticides and metabolites are typically analysed by

reversed-phase liquid chromatography. Retention is primarily controlled by the interaction between analytes and the stationary phase, which is hydrophobic. It is necessary to optimise the chromatography conditions such that appropriate retention, selectivity, and peak symmetry are achieved, including optimising the composition of the mobile phase, pH, strength of the buffer, temperature, and flow rate. It might be used for ionic compounds that do not work with the conventional reversed-phase approach.

Hydrophilic interaction liquid chromatography is useful for highly polar analytes which do not have a high affinity in reversed phase systems. The separation takes place by partitioning and adsorption in a water-rich layer over a polar stationary phase. It can be used for polar pharmaceuticals, metabolites, sugars, amino acids, and other hydrophilic compounds, but with reproducibility largely relying on mobile-phase composition and proper equilibration of the column.

Volatile and semi-volatile compounds like residual solvents, volatile organic contaminants, pesticides, hydrocarbons and derivatised pharmaceuticals are still significant to gas chromatography. It offers very good separation and can be used in combination with methods of flame-ionisation (FI), electron-capture (EC), nitrogen–phosphorus (NP) or mass-spectrometric detection. Chemical derivatisation may be needed for analysis of low volatility/temp. unstable compounds.

Supercritical fluorescent chromatography (SFC) is a combination of the properties of gas and liquid chromatography that usually employs supercritical carbon dioxide in conjunction with organic modifiers. It has low mobile-phase viscosity, thus facilitating the mass transfer, effective separation, and saving the consumption of organic solvents. Considering mass spectrometry, interface design is crucial to ensure ionisation efficiency and sensitivity due to pressure reduction, mobile phase expansion, and analyte transfers (Guillarme et al., 2018). It is highly useful in pharmaceutical analysis for fast, effective and chiral separation. It is a highly selective process that can be manipulated by the chemistry of the stationary phase, modifiers, additives, pressure and temperature. The number of applications in the areas of impurity profiling, natural product analysis, bioanalysis, and pharmaceutical quality control keeps growing (West, 2018).

Two-dimensional liquid chromatography (2D-LC) is used for mixtures that are not sufficiently separable using one-dimensional chromatography systems. Fractions in the first column are moved to a second column utilising a different separation mechanism, thus enhancing the analysis of complicated environmental mixtures, pharmaceutical impurities, biological extracts and degradation products. Improvements in modulation, control and data processing have enhanced its usefulness (Pirok et al., 2018).

Inorganic anions, cations, organic acids and other ionic compounds are separated by ion chromatography, while polymers, proteins, aggregates and macromolecules are separated by size-exclusion chromatography. Capillary electrochromatography is an analytical technique that can separate charged analytes with low sample and solvent usage and in high efficiency in a short time, but without reproducible migration times and with poor sensitivity, the capillary conditions, the buffer composition, the temperature and the electroosmotic flow need to be carefully controlled. A comparison of major techniques, strengths, limitations and applications is shown in Table 3.

Table 3. Comparative Features of Chromatographic and Separation Techniques

Technique	Best-suited analytes	Major strengths	Main limitations	Common applications
HPLC/UHPLC	Polar, non-volatile, thermally unstable compounds	High selectivity and detector compatibility	Solvent use and method-development requirements	Pharmaceuticals, pesticides, metabolites
Gas chromatography	Volatile and semi-volatile compounds	High efficiency and reproducible retention	Derivatisation may be required	Residual solvents, hydrocarbons, pesticides
Hydrophilic interaction chromatography	Highly polar compounds	Improved retention of polar analytes	Long equilibration and reproducibility issues	Metabolites, amino acids, sugars
Supercritical-fluid chromatography	Chiral and moderately non-polar compounds	Rapid analysis and reduced solvent use	Complex pressure and interface control	Chiral drugs and impurity profiling
Two-dimensional liquid chromatography	Highly complex mixtures	Very high peak capacity	Instrumental and data-processing complexity	Environmental mixtures and impurity profiling
Ion chromatography	Ionic species	Excellent selectivity for ions	Limited application to neutral compounds	Water ions and pharmaceutical counter-ions
Capillary electrophoresis	Charged and polar analytes	Low sample and solvent consumption	Lower concentration sensitivity	Peptides, proteins, drugs, and inorganic ions

Overall, the use of high efficiency columns, multidimensional separation, automation of sample introduction, decreased use of solvent and hyphenation with sophisticated detectors is becoming more common in modern chromatographic analysis. The best method should have good selectivity, sensitivity, precision, robustness, throughput and be suitable for the physicochemical properties of the analyte(s) and the nature of the sample matrix. The main analytical methods are classified, including the chromatographic, mass-spectrometric, spectroscopic, material-characterisation and sensor-based analytical methods (Figure 2).

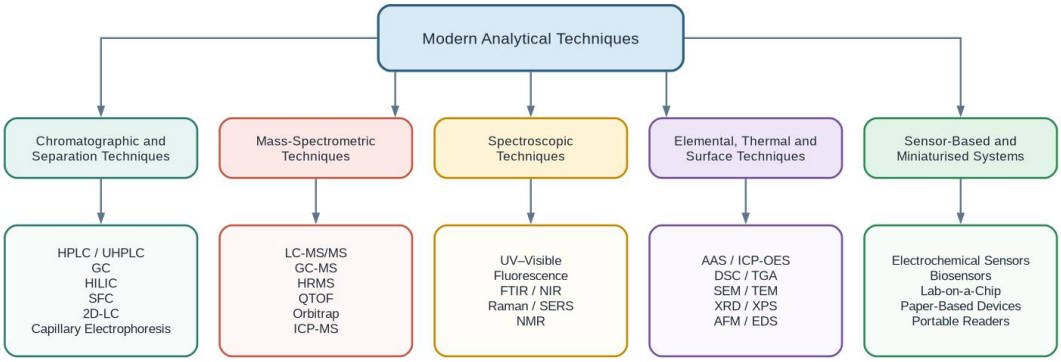

Figure 2. Classification of modern analytical techniques used for environmental and pharmaceutical sample characterisation

5. MASS SPECTROMETRY AND HYPHENATED ANALYTICAL TECHNIQUES

The technique of mass spectrometry is one of the most powerful tools to characterise environmental and pharmaceutical samples, due to its high sensitivity, molecular selectivity and structural information. It is especially well-suited to the detection of trace contaminants, pharmaceutical residues or metabolites, degradation products, impurities, or unknown compounds, in complex matrices. The technique is used to measure ions by their mass-to-charge ratio and is often used in conjunction with chromatographic separation to aid in compound identification and quantification.

Liquid chromatography–mass spectrometry plays an important role in the analysis of polar, non-volatile, thermally labile compounds such as pharmaceuticals, personal-care products, pesticides, metabolites and emerging contaminants in the environment. The first function of the liquid chromatography is to separate the analytes from the matrix components, while the second is to give information about the molecular mass and fragmentation of the analytes to the mass spectrometer. The most common interfaces used to transfer analytes from the liquid phase to gas-phase ions are electrospray ionisation and atmospheric-pressure chemical ionisation.

Analytical selectivity is further enhanced by tandem mass spectrometry, which allows a precursor ion to be isolated and the intensities of characteristic product-ion fragments to be measured. Multiple-reaction monitoring provides high sensitivity and specificity with good reproducibility; triple quadrupole instruments are popular for targeted quantitative analysis in pharmaceutical quality control, bioanalysis, toxicology, residue analysis and environmental monitoring. However, these techniques are usually dependent on prior knowledge of the target compounds and availability of suitable analytical standards.

Environmental mass spectrometry has been extended using high-resolution mass spectrometry, which can accurately measure and provide extensive chemical screening. Target and suspect monitoring methods can be used to identify a wide range of pollutants in a single sample, including those not normally monitored in standard monitoring programmes. The implementation of this method in the basin of the Dniester River highlighted the importance of the application of advanced mass-spectrometric screening for the determination of a complex pattern of chemical contamination in environmental samples (Diamanti et al., 2020).

Volatile and semi-volatile compounds, including residual solvents, hydrocarbons, pesticides, industrial chemicals and volatile degradation products, are best analysed by gas chromatography–mass spectrometry. This method of electron-ionisation fragmentation can be used to generate reproducible spectra, which can be matched to reference libraries and are very useful for determining known compounds. Must derivatise if analytes are less volatile or not suitable thermally.

Non-target screening has become more relevant as more contaminants, transformation products and impurities are found in the environment and in pharmaceuticals and are not included in targeted analytical methods. High-resolution instruments can be used to obtain accurate mass full scan information that can be used for retrospective analysis if new compounds are identified later. Studies of water analysis using a collaborative approach have demonstrated that a significant portion of the chemicals detected were not

covered by any of the individual methods, but there are difficulties with the interpretation of these data, with structural identification and with comparability between the different laboratories involved (Schymanski et al., 2015).

Suspect screening is a middle ground between targeted and full non-targeted analysis. It looks for compounds based on information, including Molecular Formula or data provided in a Database, without the use of complete Reference Standards. The integrated workflow for target, suspect and non-target mass-spectrometrical screening and compound identification is shown in Figure 3.

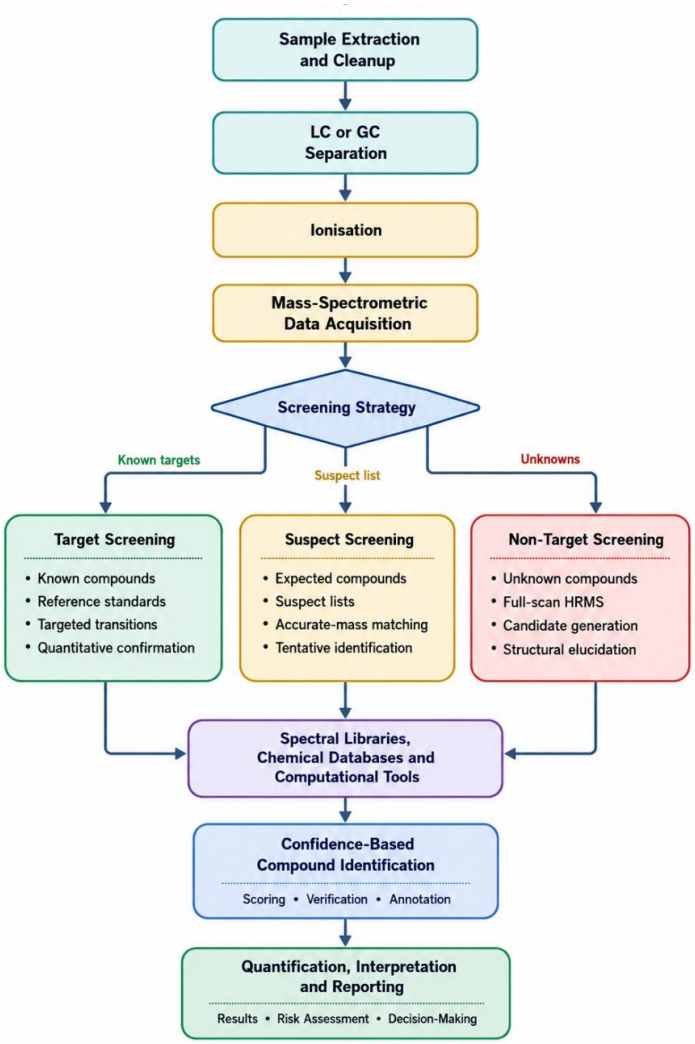

Figure 3. Mass-spectrometric workflow for target, suspect, and non-target screening, identification, and reporting

Suspect screening uses lists of expected or plausible compounds without requiring authentic reference standards during the initial screening stage. Candidate compounds are prioritised according to accurate mass, isotope patterns, retention behaviour, fragmentation characteristics, and database matches. Authentic standards and reference spectra are subsequently used to strengthen compound confirmation and improve confidence in identification.

Chemical databases and computational tools are increasingly integrated into mass-spectrometric workflows. Large chemical knowledge bases facilitate molecular-formula assignment, candidate generation, spectral matching, and prioritisation of possible structures. The combined use of PubChemLite and MetFrag has improved the interpretation of high-resolution mass-spectrometric data by providing curated chemical information that supports environmental screening and exposomics research (Schymanski et al., 2021).

Modern mass spectrometers may combine two or more analyser types within a single instrument to provide complementary analytical performance. Quadrupole time-of-flight systems offer rapid full-mass-range scanning and accurate-mass measurement, whereas Orbitrap instruments provide high resolving power and excellent mass accuracy. Ion-trap systems support multistage fragmentation and are particularly valuable for detailed structural investigation. Instrument selection therefore depends on whether the main analytical objective is routine quantification, broad chemical screening, impurity identification, metabolite characterisation, or structural confirmation.

Hyphenated mass-spectrometric systems are not limited to liquid or gas chromatography. Capillary electrophoresis–mass spectrometry is useful for ionic and highly polar analytes, while supercritical-fluid chromatography–mass spectrometry can provide rapid separations with reduced solvent consumption. Inductively coupled plasma–mass spectrometry is primarily used for elemental and isotopic analysis rather than molecular characterisation. These combinations demonstrate the flexibility of integrating separation and detection techniques to address diverse analytical challenges.

Despite their major advantages, mass-spectrometric techniques are affected by several limitations, including matrix effects, ion suppression, high instrumentation costs, complex data processing, difficulties in identifying unknown compounds, and limited availability of reference materials. Reliable quantification requires suitable calibration procedures, internal standards, quality-control samples, validated extraction methods, and appropriate analytical validation. When authentic standards or comprehensive spectral databases are unavailable, the identification of unknown compounds may remain tentative.

Overall, standalone and hyphenated mass-spectrometric techniques provide powerful capabilities for targeted quantification, suspect screening, non-target analysis, metabolite and impurity identification, and structural elucidation. Their role in environmental monitoring and pharmaceutical characterisation is expected to expand further through improvements in resolving power, ionisation efficiency, database quality, computational software, and automated data interpretation.

6. SPECTROSCOPIC TECHNIQUES

Spectroscopic techniques are widely used for the chemical characterisation of environmental and pharmaceutical samples because they provide valuable information on molecular structure, chemical composition, functional groups, bonding, and analyte concentration. Most spectroscopic methods are rapid, require minimal sample preparation, and can be applied to compound identification, impurity detection, quantitative analysis, process monitoring, raw-material verification, and structural elucidation.

Ultraviolet–visible (UV–Vis) spectroscopy is one of the most accessible analytical techniques and measures the absorption of ultraviolet or visible radiation by chromophore-containing molecules. It is extensively used for pharmaceutical assays, dissolution studies, reaction monitoring, and the analysis of coloured environmental pollutants. Although it offers rapid analysis, simple operation, and relatively low instrumentation cost, its application to complex mixtures may be limited by spectral overlap unless combined with separation techniques or chemometric analysis.

Fluorescence spectroscopy provides greater sensitivity than conventional absorbance measurements for naturally fluorescent compounds and is widely applied to trace analysis of pesticides, aromatic pharmaceuticals, biological molecules, and environmental contaminants. Non-fluorescent analytes can also be analysed after suitable derivatisation. However, fluorescence intensity is affected by factors such as pH, temperature, solvent composition, quenching agents, and matrix effects, requiring careful optimisation and calibration.

Infrared (IR) spectroscopy provides molecular information through vibrational absorption, while Fourier-transform infrared (FTIR) spectroscopy is extensively used for functional-group identification, raw-material verification, drug–excipient compatibility studies, polymer characterisation, and monitoring chemical changes during degradation or processing. Attenuated total reflectance (ATR) accessories enable direct analysis of powders, tablets, liquids, films, and surfaces with minimal preparation. Near-infrared (NIR) spectroscopy further supports rapid, non-destructive evaluation of pharmaceutical raw materials and finished dosage forms by determining moisture content, active ingredient concentration, blend uniformity, coating thickness, particle characteristics, and manufacturing endpoints. Because NIR spectra contain broad, overlapping bands, multivariate calibration methods are generally required for quantitative analysis.

Raman spectroscopy complements infrared techniques by providing vibrational information that is particularly useful for compounds containing non-polar bonds or symmetrical molecular structures. Its weak interference from water enables direct analysis of aqueous samples, making it valuable for pharmaceutical identification, polymorph discrimination, counterfeit medicine detection, microplastic characterisation, and analysis through transparent packaging. The increasing availability of portable Raman instruments has further expanded field applications. Surface-enhanced Raman spectroscopy (SERS) significantly improves analytical sensitivity by using nanostructured metallic substrates to enhance Raman signals, enabling detection of analytes at extremely low concentrations in pharmaceutical, biomedical, and environmental applications. Despite advances in substrate design and signal enhancement, substrate reproducibility and quantitative standardisation remain major limitations (Cialla-May et al., 2017).

Portable infrared and Raman instruments have become increasingly important for the rapid screening of falsified and substandard medicines. These systems enable fast, non-destructive comparison of suspicious products with reference materials in field settings, although confirmatory laboratory testing is generally

required for regulatory or legal purposes (Kammrath et al., 2023). Vibrational spectroscopic techniques also support green analytical chemistry by minimising sample preparation, solvent consumption, reagent use, laboratory waste, and analysis time. Their quantitative performance is substantially enhanced through chemometric tools such as principal component analysis (PCA), partial least-squares regression (PLS), and classification models (Moros et al., 2010).

Nuclear magnetic resonance (NMR) spectroscopy remains one of the most powerful methods for molecular structure elucidation, providing information on chemical environment, molecular connectivity, stereochemistry, and molecular dynamics. In pharmaceutical analysis, NMR is applied to identity confirmation, impurity profiling, metabolite characterisation, structural elucidation, and quantitative analysis without compound-specific response factors. Atomic absorption and atomic emission spectroscopy are primarily employed for elemental determination in environmental and pharmaceutical samples, particularly for toxic metals, catalyst residues, mineral content, and elemental impurities.

Overall, spectroscopic techniques provide rapid, versatile, and information-rich analysis for environmental and pharmaceutical characterisation. Continued advances in portable instrumentation, fibre-optic probes, nanostructured sensing platforms, automated spectral processing, digital spectral libraries, and chemometric modelling have further expanded their analytical capabilities. Although some methods remain limited by spectral overlap or sensitivity, their speed, minimal sample consumption, and non-destructive nature ensure their continued importance in modern analytical science.

7. ELEMENTAL, THERMAL, AND SURFACE CHARACTERIZATION TECHNIQUES

Elemental, thermal and surface characterisation methods are vital in terms of the information they provide to environmental and pharmaceutical samples about their composition, stability, morphology, structure and physicochemical behaviour. The techniques are especially useful when the analytical goal is not just to identify a molecule, but also to characterise the chemical nature of elements, inorganic contaminants, thermal degradation, particle properties, the surface chemistry and interactions of materials, crystallinity, and material interactions. A combination of these two applications can give significant information on complex samples, which is more than one could obtain from either of the analytical methods alone. The combined use and synergy of the elemental, thermal, morphological, structural and surface analyses is illustrated in Figure 4 and can be used effectively for material characterisation.

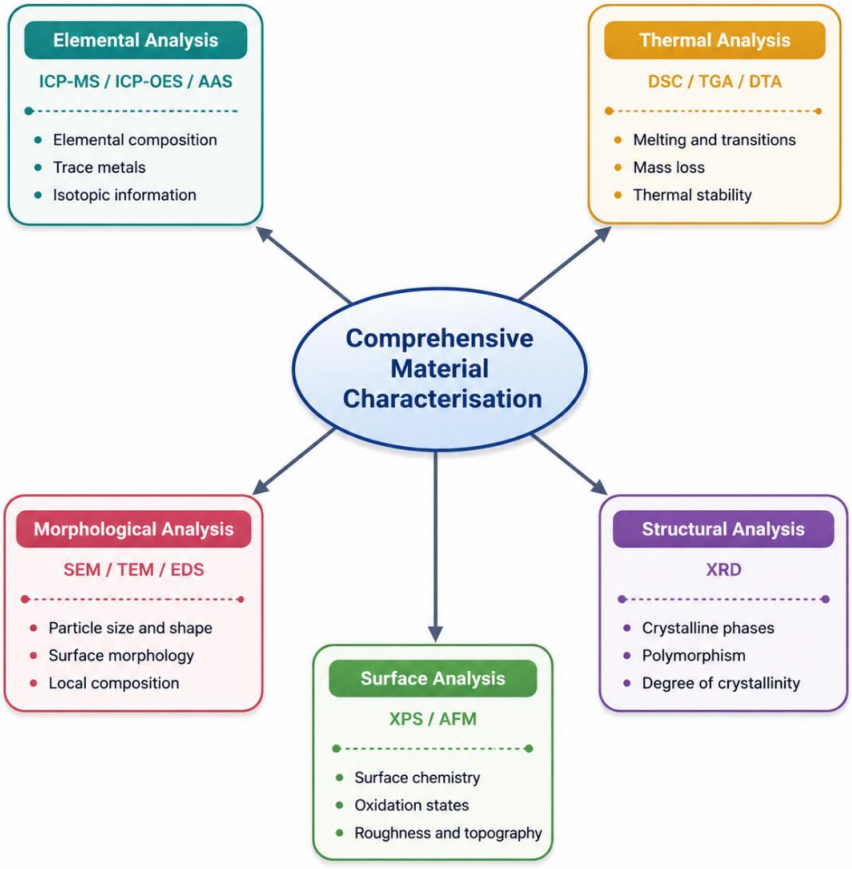

Figure 4. Integrated framework of elemental, thermal, morphological, structural, and surface-characterisation techniques

Elemental analysis is essential for determining toxic metals, essential elements, catalyst residues, mineral components, and trace elements in environmental and pharmaceutical samples. Environmental matrices may contain elements originating from geological sources, industrial discharge, mining, agriculture, and atmospheric deposition. In pharmaceuticals, elemental impurities may arise from raw materials, catalysts, equipment, excipients, packaging, or storage. Accurate measurement is therefore necessary for environmental risk assessment, quality control, and regulatory compliance.

Inductively coupled plasma–mass spectrometry (ICP–MS) is one of the most sensitive techniques for multielement analysis. Samples are introduced into high-temperature plasma, where atoms are ionised and separated according to their mass-to-charge ratios. ICP–MS provides low detection limits, broad linear ranges, rapid multielement analysis, and isotope-specific information, making it suitable for water, wastewater, soil extracts, biological samples, active pharmaceutical ingredients, and finished products. Spectral interferences may occur when ions have similar nominal masses. Tandem ICP–MS addresses this problem using two mass-selection stages separated by a collision or reaction cell, improving elemental determination in complex matrices (Bolea-Fernandez et al., 2017).

Atomic absorption spectroscopy is another widely used method. Flame atomic absorption is suitable for moderate concentrations, whereas graphite-furnace atomic absorption provides greater sensitivity for trace elements. These techniques are relatively simple and economical but slower than simultaneous multielement methods. Inductively coupled plasma–optical emission spectrometry measures radiation emitted by excited atoms and ions and offers rapid analysis, broad elemental coverage, and tolerance of relatively concentrated samples. It is widely used for pharmaceutical raw materials, wastewater, soil digests, minerals, and industrial samples.

Technology-critical elements, including rare earth elements, gallium, germanium, indium, and platinum-group metals, are increasingly important because of their use in electronics, renewable-energy technologies, medical devices, and catalysts. Their environmental release and possible health effects require reliable monitoring in water, soil, sediment, and biological matrices (Cobelo-García et al., 2015).

Thermal techniques provide information on material behaviour during controlled heating or cooling. Thermogravimetric analysis measures changes in mass and can assess moisture, solvent loss, decomposition, oxidation, ash content, and thermal stability. Differential scanning calorimetry measures heat-flow changes associated with melting, glass transitions, crystallisation, polymorphic transformations, and drug–excipient interactions. Differential thermal analysis and simultaneous thermal analysis provide complementary information, while coupling thermal analysis with infrared spectroscopy or mass spectrometry helps identify gases released during decomposition.

Surface and morphological techniques assess particle size, shape, porosity, roughness, and surface composition. Scanning electron microscopy is used for pharmaceutical powders, tablets, coatings, nanoparticles, sediments, and microplastics, often with energy-dispersive X-ray spectroscopy for local elemental analysis. Transmission electron microscopy provides higher-resolution information on nanoparticle size, structure, aggregation, and internal organisation. Because no single method fully describes nanoparticle properties, multiple complementary techniques are required (Mourdikoudis et al., 2018).

X-ray diffraction identifies crystalline phases, polymorphs, salts, hydrates, amorphous forms, and minerals. X-ray photoelectron spectroscopy determines surface elemental composition and chemical states, while atomic force microscopy measures nanoscale topography, roughness, and mechanical properties. Reliable ICP–MS analysis also requires suitable digestion, internal standards, blanks, certified reference materials, and recovery studies (Wilschefski & Baxter, 2019). Together, these methods provide complementary information on composition, structure, stability, and material behaviour.

8. APPLICATIONS IN PHARMACEUTICAL ANALYSIS

Modern analytical technologies are instrumental in the development, production, quality control and compliance of pharmaceuticals. They can be used to confirm the identity of the drug, measure the potency, detect any impurities, assess drug degradation, determine the dissolution behaviour, and test for consistency of the raw material or finished product.

HPLC and UHPLC methods are widely used for the assay determination, impurity profiling, stability and content uniformity studies. The identification of trace impurities, metabolites and degradation products is achieved with higher sensitivity and structural information by mass spectrometry. Infrared, Raman, and near-infrared spectroscopy are spectroscopic methods that are used to evaluate pharmaceutical materials rapidly and often without causing any damage to them.

Analytical method lifecycle management is more crucial than ever as pharmaceutical methods need to be reliable throughout the development, validation, transfer, routine and continuous improvement phases. A lifecycle approach improves the robustness of the methods, risk management, compliance with regulations,

and analytical performance in the long run (Volta and Sousa, 2021).

PAT is also being used as a tool to revolutionise pharmaceutical manufacturing by allowing for the real-time monitoring of blending, granulation, drying, compression, and coating. For pharmaceutical manufacturing, the future is increasingly one of continuous manufacturing, automated control, advanced modelling, and integrated analytical systems that help to maintain product consistency and enhance manufacturing efficiencies (Rantanen & Khinast, 2015).

Reliable measurements of critical material properties and process parameters are needed for continuous manufacturing. In-line tools like near infrared spectroscopy can deliver speedy data about blend uniformity, active pharmaceutical ingredient concentration, moisture and tablet quality properties during production. They are successfully applied in solid dosage forms as real-time analytical monitoring to aid process control and final product assurance (Roggo et al., 2020). The main uses and analytical data obtained with the modern techniques in environmental and pharmaceutical analysis are summarised in Table 4.

Table 4. Analytical Techniques and Their Major Applications in Environmental and Pharmaceutical Analysis

Analytical technique	Environmental applications	Pharmaceutical applications	Main information obtained
LC-MS/MS	Pharmaceuticals, pesticides, emerging contaminants	Drug assay, metabolites, impurity analysis	Sensitive quantification and structural confirmation
GC-MS	Volatile pollutants and hydrocarbons	Residual solvents and volatile impurities	Compound identification and fragmentation
FTIR spectroscopy	Microplastics, organic matter, contaminated solids	Raw-material identification and compatibility studies	Functional groups and molecular identity
Raman spectroscopy	Microplastics and field pollutant screening	Polymorphs, counterfeit medicines, API identification	Molecular vibration and structural information
ICP-MS	Metals and technology-critical elements	Elemental impurities and catalyst residues	Trace elemental composition
DSC/TGA	Polymer and microplastic characterisation	Thermal stability and drug–excipient interaction	Thermal transitions and decomposition
Electrochemical sensors	Heavy metals, pesticides, and pathogens	Drug detection and point-of-care analysis	Rapid concentration-dependent electrical response
NIR spectroscopy	Limited environmental screening	Blend uniformity and process monitoring	Rapid non-destructive quantitative information

Finally, the combination of chromatography and spectroscopy, mass spectrometry, and process-monitoring technologies enhances pharmaceutical quality assurance. These techniques provide enhanced control of impurities, manufacturing consistency, regulatory compliance and development of safer and more effective medicines.

9. DATA PROCESSING, CHEMOMETRICS, AND METHOD VALIDATION

Analytical techniques of the modern era produce large and complex data sets, which must be processed systematically to make meaningful sense of them. Baseline correction, normalisation, smoothing, peak alignment, scaling, transformation and instrumental noise removal are potential data preprocessing methods. These steps help to increase the quality of the data and minimise any unwanted variation without changing the chemical information in the data.

While statistical analysis and machine-learning methods are both important in the field of analytical science, they are complementary. While conventional statistics are usually applied to inference, hypothesis testing and interpretation, machine-learning methods are typically applied to high-dimensional datasets for prediction, classification, and pattern recognition (Bzdok et al., 2018).

The use of chemometric techniques in chromatographic, spectroscopic, metabolomic and sensor data is very common. Principal component analysis can be used to identify sources of variation, or to visualise the relation between samples which are dominant. Partial least-squares regression can be used for quantitative prediction, and partial least-squares discriminant analysis is often employed for classification. But the improper construction of these models can lead to overfitting and to non-representative discrimination, which is why it is important to validate the models (Gromski et al., 2015).

The validation of an analytical method ensures that the method can be used for its intended purpose. Common parameters are specificity, accuracy, precision, linearity, range, detection limit, quantification limit and robustness. The ICH Q2(R1) guideline provided a harmonised guideline to assess these performance criteria in pharmaceutical analytical procedures (International Council for Harmonisation of Technical

Requirements for Pharmaceuticals for Human Use, 2005).

The revised ICH Q2(R2) guideline also reiterates the science-based approach to validation, lifecycle approach, risk assessment and proper application of multivariate analytical procedures. It provides for more flexible approaches towards validation strategy but retains the reliability and the regulatory acceptability of analytical results (Ermer, 2025). The main parameters and chemometric methods of the method validation and the reliability and interpretability of the analytical result are summarised in Table 5.

Table 5. Major Method-Validation and Chemometric Parameters

Parameter or method	Purpose	Typical evaluation criterion
Specificity	Distinguishes analyte from interferences	Absence of interfering response
Accuracy	Measures closeness to the true value	Recovery percentage
Precision	Assesses repeatability and reproducibility	Relative standard deviation
Linearity	Evaluates proportionality between signal and concentration	Regression coefficient and residual analysis
Detection limit	Lowest detectable concentration	Signal-to-noise or statistical estimate
Quantification limit	Lowest reliably measurable concentration	Precision and accuracy at low concentration
Robustness	Assesses resistance to small method changes	Stability under altered conditions
Principal component analysis	Identifies patterns and dominant variation	Scores and loading plots
Partial least-squares regression	Predicts analyte concentration	Calibration and validation error
Cross-validation	Tests model generalisability	Prediction error and model stability

Overall, reliable chemical characterisation depends not only on advanced instrumentation but also on appropriate data processing, validated chemometric models, and well-designed method-validation procedures. These components ensure that analytical results are accurate, reproducible, interpretable, and suitable for environmental or pharmaceutical decision-making.

10. CONCLUSION

Complex environmental and pharmaceutical samples can be characterised with a range of increasingly integrated analytical techniques in modern analytical science. To depend on these reliable analyses, representative sampling, proper preservation, efficient extraction, selective cleanup, and effective control of the matrix effects must be considered. Chromatographic and electrophoretic techniques still form the backbone of separation for complex mixtures, with tandem or sensitive high-resolution mass spectrometry providing the additional tools to allow sensitive quantification of components, extensive screening of the mixture, identification of impurities and structural confirmation. Spectroscopic methods are used to quickly and sometimes non-destructively determine the composition of molecules, raw materials, dosage forms, contaminants, and process parameters. Elemental, thermal, structural, morphological and surface techniques give complementary information about the properties of the trace metals, crystallinity, polymorphism, stability, particle properties and interactions with the material. Rapid, decentralised, low-volume analysis is also facilitated by electrochemical sensors, biosensors, lab-on-a-chip systems and portable platforms. There are, however, several significant issues such as complex matrices, ion suppression, incomplete spectral libraries, limited reference standards, high instrumentation costs, inconsistent protocols and difficulties with data interpretation. A robust method validation, certified reference materials, internal standards, chemometric validation and interlaboratory harmonisation are therefore necessary. Going forward, future developments will integrate miniaturised instrumentation systems, real-time monitoring systems, automation and the inclusion of artificial intelligence, digital twins and green sample preparation, which will increase the analytical se**nsitivity, sustainability, accessibility, reproducibility and regulatory trust and certitude in environmental protection,** pharmaceutical quality assurance and public-health decision-making.

REFERENCES

1. Aus der Beek, T., Weber, F. A., Bergmann, A., Hickmann, S., Ebert, I., Hein, A., & Küster, A. (2016). Pharmaceuticals in the environment—Global occurrences and perspectives. Environmental toxicology and chemistry, 35(4), 823-835.
2. Kümmerer, K., Dionysiou, D. D., Olsson, O., & Fatta-Kassinos, D. (2019). Reducing aquatic micropollutants–Increasing the focus on input prevention and integrated emission management. Science of the Total Environment, 652, 836-850.

3. Richardson, S. D., & Kimura, S. Y. (2019). Water analysis: emerging contaminants and current issues. Analytical Chemistry, 92(1), 473-505.
4. Wilkinson, J. L., Boxall, A. B., Kolpin, D. W., Leung, K. M., Lai, R. W., Galbán-Malagón, C., ... & Teta, C. (2022). Pharmaceutical pollution of the world's rivers. Proceedings of the national academy of sciences, 119(8), e2113947119.
5. Gosetti, F., Mazzucco, E., Zampieri, D., & Gennaro, M. C. (2010). Signal suppression/enhancement in high-performance liquid chromatography tandem mass spectrometry. Journal of Chromatography A, 1217(25), 3929-3937.
6. Alqarni, A. M. (2024). Analytical methods for the determination of pharmaceuticals and personal care products in solid and liquid environmental matrices: A review. Molecules, 29(16), 3900.
7. Panuwet, P., Hunter Jr, R. E., D'Souza, P. E., Chen, X., Radford, S. A., Cohen, J. R., ... & Barr, D. B. (2016). Biological matrix effects in quantitative tandem mass spectrometry-based analytical methods: advancing biomonitoring. Critical reviews in analytical chemistry, 46(2), 93-105.
8. Cappiello, A., Famiglini, G., Palma, P., & Trufelli, H. (2010). Matrix effects in liquid chromatography-mass spectrometry. Journal of liquid chromatography & related technologies, 33(9-12), 1067-1081.
9. Ahmad, W., Al-Sibaai, A. A., Bashammakh, A. S., Alwael, H., & El-Shahawi, M. S. (2015). Recent advances in dispersive liquid-liquid microextraction for pesticide analysis. TrAC Trends in Analytical Chemistry, 72, 181-192.
10. Hashemi, B., Zohrabi, P., Kim, K. H., Shamsipur, M., Deep, A., & Hong, J. (2017). Recent advances in liquid-phase microextraction techniques for the analysis of environmental pollutants. TrAC Trends in Analytical Chemistry, 97, 83-95.
11. Santana-Mayor, A., Rodríguez-Ramos, R., Herrera-Herrera, A. V., Socas-Rodríguez, B., & Rodríguez-Delgado, M. A. (2023). Updated overview of QuEChERS applications in food, environmental and biological analysis (2020–2023). TrAC Trends in Analytical Chemistry, 169, 117375.
12. Ścigalski, P., & Kosobucki, P. (2020). Recent materials developed for dispersive solid phase extraction. Molecules, 25(21), 4869.
13. Desmet, G., & Broeckhoven, K. (2019). Extra-column band broadening effects in contemporary liquid chromatography: Causes and solutions. TrAC Trends in Analytical Chemistry, 119, 115619.
14. Guillarme, D., Desfontaine, V., Heinisch, S., & Veuthey, J. L. (2018). What are the current solutions for interfacing supercritical fluid chromatography and mass spectrometry?. Journal of Chromatography B, 1083, 160-170.
15. Pirok, B. W., Stoll, D. R., & Schoenmakers, P. J. (2018). Recent developments in two-dimensional liquid chromatography: fundamental improvements for practical applications. Analytical Chemistry, 91(1), 240-263.
16. West, C. (2018). Current trends in supercritical fluid chromatography. Analytical & Bioanalytical Chemistry, 410(25), 6441.
17. Diamanti, K. S., Alygizakis, N. A., Nika, M. C., Oswaldova, M., Oswald, P., Thomaidis, N. S., & Slobodnik, J. (2020). Assessment of the chemical pollution status of the Dniester River Basin by wide-scope target and suspect screening using mass spectrometric techniques. Analytical & Bioanalytical Chemistry, 412(20), 4893.
18. Singh, V., Kashif, M., Ubaid, S., Singh, T., Pahwa, R., Singh, A. K., & Singh, A. (2025). Advancements in High-Performance Liquid Chromatography: Transforming Analytical Chemistry Across Biomedical, Pharmaceutical, and Environmental Domains. In Advanced Biophysical Techniques in Biosciences (pp. 137-167). Cham: Springer Nature Switzerland.
19. Schymanski, E. L., Singer, H. P., Slobodnik, J., Ipolyi, I. M., Oswald, P., Krauss, M., ... & Hollender, J. (2015). Non-target screening with high-resolution mass spectrometry: critical review using a collaborative trial on water analysis. Analytical and bioanalytical chemistry, 407, 6237-6255.
20. Schymanski, E. L., Kondić, T., Neumann, S., Thiessen, P. A., Zhang, J., & Bolton, E. E. (2021). Empowering large chemical knowledge bases for exposomics: PubChemLite meets MetFrag. Journal of Cheminformatics, 13(1), 19.
21. Cialla-May, D., Zheng, X. S., Weber, K., & Popp, J. J. C. S. R. (2017). Recent progress in surface-enhanced Raman spectroscopy for biological and biomedical applications: from cells to clinics. Chemical Society Reviews, 46(13), 3945-3961.
22. Kammrath, B. W., Leary, P. E., & Crocombe, R. A. (2023). Detection and analysis of counterfeit drugs. Trends in Counterfeit drugs, 87-144.
23. Moros, J., Garrigues, S., & de la Guardia, M. (2010). Vibrational spectroscopy provides a green tool for multi-component analysis. TrAC Trends in Analytical Chemistry, 29(7), 578-591.
24. Ozaki, Y., Huck, C., Tsuchikawa, S., & Engelsen, S. B. (Eds.). (2021). Near-infrared spectroscopy:

theory, spectral analysis, instrumentation, and applications (Vol. 202, No. 1, pp. 1-25). Singapore: Springer.
25. Bolea-Fernandez, E., Balcaen, L., Resano, M., & Vanhaecke, F. (2017). Overcoming spectral overlap via inductively coupled plasma-tandem mass spectrometry (ICP-MS/MS). A tutorial review. Journal of Analytical Atomic Spectrometry, 32(9), 1660-1679.
26. Cobelo-García, A., Filella, M., Croot, P., Frazzoli, C., Du Laing, G., Ospina-Alvarez, N., ... & Zimmermann, S. (2015). COST action TD1407: network on technology-critical elements (NOTICE)—from environmental processes to human health threats. Environmental Science and Pollution Research, 22(19), 15188-15194.
27. Mourdikoudis, S., Pallares, R. M., & Thanh, N. T. (2018). Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties. Nanoscale, 10(27), 12871-12934.
28. Wilschefski, S. C., & Baxter, M. R. (2019). Inductively coupled plasma mass spectrometry: introduction to analytical aspects. The Clinical Biochemist Reviews, 40(3), 115.
29. Bhatt, P., Pathak, V. M., Bagheri, A. R., & Bilal, M. (2021). Microplastic contaminants in the aqueous environment, fate, toxicity consequences, and remediation strategies. Environmental Research, 200, 111762.
30. Finotti Cordeiro, C., Lopardi Franco, L., Teixeira Carvalho, D., & Bonfilio, R. (2026). Impurities in active pharmaceutical ingredients and drug products: A critical review. Critical Reviews in Analytical Chemistry, 56(1), 55-75.
31. Volta e Sousa, L., Gonçalves, R., Menezes, J. C., & Ramos, A. (2021). Analytical method lifecycle management in pharmaceutical industry: a review. Aaps Pharmscitech, 22(3), 128.
32. Rantanen, J., & Khinast, J. (2015). The future of pharmaceutical manufacturing sciences. Journal of pharmaceutical sciences, 104(11), 3612-3638.
33. Roggo, Y., Pauli, V., Jelsch, M., Pellegatti, L., Elbaz, F., Ensslin, S., ... & Krumme, M. (2020). Continuous manufacturing process monitoring of pharmaceutical solid dosage form: A case study. Journal of pharmaceutical and biomedical analysis, 179, 112971.
34. Ij, H. (2018). Statistics versus machine learning. Nat Methods, 15(4), 233.
35. Gromski, P. S., Muhamadali, H., Ellis, D. I., Xu, Y., Correa, E., Turner, M. L., & Goodacre, R. (2015). A tutorial review: Metabolomics and partial least squares-discriminant analysis–a marriage of convenience or a shotgun wedding. Analytica chimica acta, 879, 10-23.
36. Guideline, I. H. T. (2005). Validation of analytical procedures: text and methodology. Q2 (R1), 1(20), 05.
37. Ermer, J. (2025). ICH Q2 (R2): validation of analytical procedures. Method validation in pharmaceutical analysis: a guide to best practice, 351-372.
38. Sajid, M., & Płotka-Wasylka, J. (2022). Green analytical chemistry metrics: A review. Talanta, 238, 123046.