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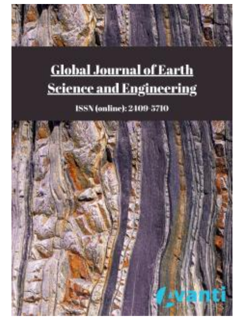

Advanced Analytical Methods for Forensic Water Quality Assessment: A PRISMA-Based Systematic Review of Trace Metals, PFAS, Microbial Source Tracking, and Field Sensors

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ABSTRACT

Forensic water quality assessment has become a critical interdisciplinary field linking environmental science, public health and legal accountability. Traditional monitoring techniques often lack the sensitivity and admissibility needed for litigation, driving demand for advanced analytical tools. This review synthesises recent innovations, including inductively coupled plasma mass spectrometry (ICP-MS), gas chromatography, DNA-based microbial source tracking, isotopic fingerprinting and portable electrochemical sensors. These techniques enable ultra-trace detection, source attribution and rapid in-field screening of both conventional and emerging pollutants such as PFAS, pharmaceuticals and pathogens. Results underscore strengths and limitations, emphasising challenges of weathering effects, marker decay, calibration stability and emerging analyte lists. By employing the PRISMA framework, this study integrates evidence across fifty-three (53) key investigations, highlighting how analytical advancements strengthen regulatory enforcement, courtroom defensibility and sustainable water governance. Collectively, modern forensic approaches offer robust pathways to safeguard communities against pollution threats. The implications of forensic water quality assessment extend beyond science, directly supporting the United Nations Sustainable Development Goals (SDGs), especially SDG 6 (Clean-Water and Sanitation), SDG 3 (Good health and Well-Being) and SDG 16 (Peace, Justice and Strong Institutions), by linking advanced monitoring with public health protection and legal accountability.

1. Introduction

Water is both a vital natural resource and a potential medium of environmental crime [1]. Illegal waste disposal, industrial discharge, oil spills and deliberate pollution events represent major threats not only to ecosystems and public health but also to legal systems tasked with accountability [2, 3]. Conventional water quality monitoring techniques, though useful, often lack the sensitivity and forensic admissibility required for legal proceedings. Therefore, analytical advancements have been instrumental in bridging environmental science with forensic science [4]. Recent innovations in trace metals detection, molecular biology and real-time monitoring have enabled forensic investigators to detect pollutants at ultra-trace levels, attribute contamination to specific sources, and offer evidence admissible in court [5, 6]. This review explores the evolution of these techniques, evaluating their strengths, limitations and forensic relevance in water quality evaluation.

Forensic water quality assessment has emerged as a critical field at the interface of environmental science, public health and legal accountability. Conventional techniques focused basically on detecting trace metals and traditional pollutants, yet rapid industrialisation, agricultural expansion and urbanisation have introduced novel categories of pollutants, including pharmaceuticals, personal care products, macro plastics and endocrine-disrupting compounds [7, 8]. These evolving contaminants demand more sensitive, selective and high-resolution analytical techniques than traditional monitoring techniques can offer.

Recent advances in analytical instrumentation – such as inductively coupled plasma mass spectrometry (ICP-MS) for trace metals, gas chromatography-mass spectrometry (GC-MS) [9, 10] and liquid chromatography-tandem mass spectrometry (LCMS/MS) for organic pollutants and DNA-based microbial source tracking-have considerably expanded the scope and reliability of forensic investigations. Coupled with real-time sensors and portable devices, these tools allow rapid detection, source attribution and temporal monitoring of pollutants in various aquatic environments.

A systematic review of these advances is timely, since it underscores how modern forensic water quality assessment not only improves environmental monitoring but also supports legal processes, strengthens regulatory frameworks and informs public health interventions [11, 12]. Hence, by synthesising knowledge across disciplines, this review offers a comprehensive understanding of how cutting-edge existing gaps in detecting, quantifying and tracing contaminants. Eventually, the study highlights the role of advanced forensic methods in achieving sustainable water management and safeguarding communities against both conventional and emerging water quality threats. Fig. (**1**) (Infographic) demonstrates the interdisciplinary nature of forensic water analysis, integrating environmental science, public health and legal accountability. Advanced analytical tools, including ICP-MS, LC-MS/MS, DNA source tracking, isotopic fingerprinting and real-time sensors, are positioned as central to

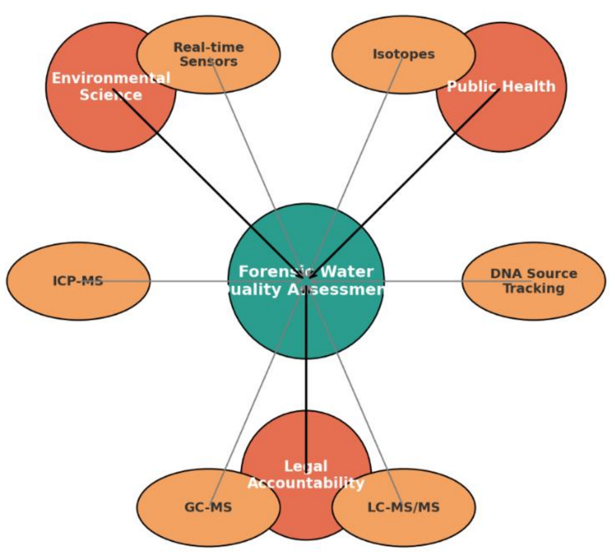

Figure 1: Conceptual framework of forensic water quality assessment.

linking science with legal evidence and policy actions. Framing these innovations within the SDG agenda highlights their wider significance; ensuring access to clean water (SDG 6), protecting community health (SDG 3), promoting responsible industrial practices (SDG 12) and reinforcing institutional justice systems (SDG 16). These connections highlight the global relevance of forensic water quality assessment in sustainable development.

2. Methodology

2.1. PRISMA Reporting and Search Strategy

To achieve methodological transparency, reproducibility, and exhaustiveness of pertinent literature, this systematic review followed the reporting principles of the PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses) 2020 guidelines [13, 14]. The PRISMA framework offers a systematic approach to systematic reviews, which is why the literature identification, screening, and inclusion are present and transparent. The review was conducted in accordance with the four PRISMA phases that included identification, screening, eligibility, and final inclusion [15, 16]. All the steps of the selection process were properly recorded and demonstrated in the PRISMA flow diagram at Fig. (**2**) of the manuscript. This systematic review reduced selection bias and increased the methodological quality of the review.

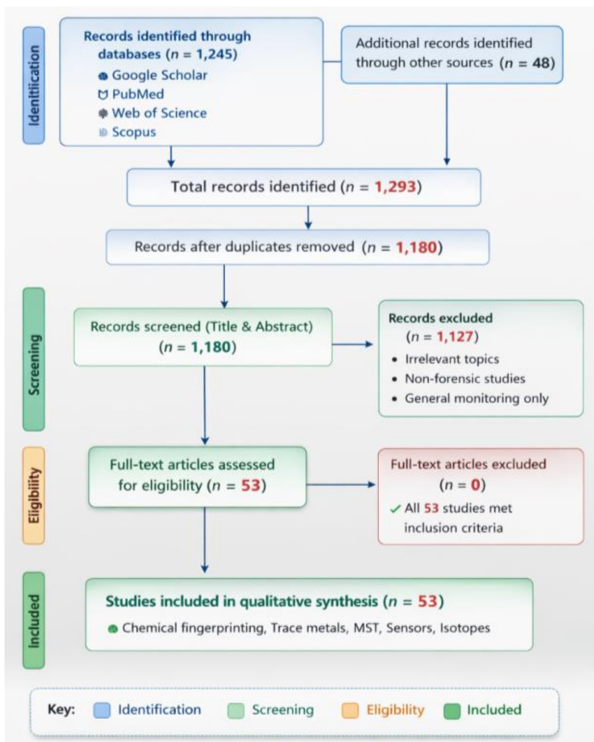

Figure 2: PRISMA flow Diagram showing study methodology.

To achieve transparency and reproducibility, the method of the study selection was based on the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA). One thousand two hundred and ninety-three (1,293) records were first discovered by searching databases and other sources. Following the elimination of duplicates, 1,180 records were left and filtered according to titles and abstracts. The screening phase reduced the number of records to 1,127 that were not relevant to forensic hydrochemistry, did not focus on forensic issues, or non-water matrices. The rest of the 53 articles were evaluated based on full-text eligibility. The 53 studies were all included in the qualitative synthesis that was made in Table **1**.

2.2. Database Search Strategy

The search of the literature was carried out in four large academic databases, which are commonly regarded as researching environmental science, public health, and forensic science. These databases were Google Scholar, PubMed, Web of science and Scopus. These sources have been chosen due to their combined coverage of the multidisciplinary studies regarding the application of analytical chemistry, environmental monitoring and forensic science applications [17, 18]. The search aim was to find papers that have undertaken the investigation of advanced analytical techniques that are applicable in forensic water quality investigations, especially the papers that have investigated the use of these techniques in detecting contaminants, the source of pollution and also the analytical techniques that can yield evidence that can be legally defended.

The search in the database was made between January 2025 and November 2025. Nonetheless, the period of publications of eligible studies was narrowed to articles published in the range between January 1990 and December 2025. This is a period of time that was chosen because most of the modern analytical tools applicable in environmental forensic investigations, such as gas chromatography-mass spectrometry (GC-MS), inductively coupled plasma mass spectrometry (ICP-MS), microbial source tracking with DNA markers, and isotope-based tracing, were widely used in the environmental laboratory starting in the 1990s [19, 20]. Incorporation of research studies in this decade enabled the review to reflect both the basic research and the current innovations in methodologies.

The search queries were formulated based on the combination of the keywords and Boolean operators to ensure maximum sensitivity of the search as well as relevancy to research objectives. The keywords were obtained based on the key themes of the review, which included forensic water analysis, methods of analysis, tracing of environmental contamination, and sophisticated instruments in the detection of contaminants [21-23]. Database-specific indexing systems and controlled vocabulary were also used where possible to increase search precision. Certain databases, such as title and abstract field restrictions, were made to guarantee that the studies retrieved focused specifically on the analysis of water quality related to forensics, as opposed to environmental monitoring in general.

2.3. Other Search Procedures

Besides searching the database, the use of additional search strategies were used to cover the literature comprehensively and minimise any publication bias. The reference lists of some of the review papers and powerful studies that were cited by the database search were vetted by hand, in order to find further useful publications that could be absent in the initial search queries [24, 25]. This type of backward citation tracking approach allowed identifying the background studies and methodological papers that were often mentioned in the sphere of environmental forensics.

Besides, selected grey literature sources were also examined when they contained pertinent methodological pieces of information on the use of various forensic techniques for analysing water. These were technical reports and methodology guidance documents that dealt with environmental forensic investigations [26, 27]. Although peer-reviewed articles were used in the centre of the systematic synthesis, these other sources assisted in putting the new analytical methods into perspective and gave some background information on how the forensic water monitoring methods were operationalised.

2.4. Screening and Selection of the Study

The selection of the study was done in a multi-stage screening procedure based on PRISMA guidelines [28, 29]. Once all the records were obtained in the databases of choice, the reference list was prepared, and references were eliminated through a reference management program. After the elimination of duplicates, 1,180 unique records were left behind of the initially identified 1,293 studies located by the database searches and additional sources.

The initial screening process was based on assessing article titles and abstracts with the aim of deciding their suitability for the purpose of the review [30, 31]. The studies were selected because they covered analytical methods which can be applied to water quality evaluation concerning a forensic or investigative aspect. At this point, articles that concentrated only on routine monitoring of the environment but did not involve identifying the source of contaminants and a forensic interpretation were excluded. On the same note, analyses that were not related to the aquatic environmental system or those that did not involve the development of analytical studies in laboratories and their application in the environment were also eliminated. Due to this screening step, 950 records were eliminated, and 230 articles remained eligible for full-text assessment.

2.5. Eligibility Evaluation and Inclusion Criteria

Full-text articles were then filtered by pre-set inclusion criteria that were aimed at filtering out studies that had no apparent relevance to the investigations on the forensic water quality. Research papers were eligible in case they used or tested analytical methods that could identify contaminants, the source of pollution, or reinforce environmental forensic research [32, 33]. The studies that were also eligible should have involved environmental matrices like surface water, groundwater, wastewater or sediments connected with aquatic contamination. Moreover, the review was limited to peer-reviewed scientific publications that were in English in order to maintain consistency in the methodological reporting and quality of scientific publications [34, 35]. Papers that provide analytical evidence in the form of detailed analysis were given priority to be included due to their interest in forensic evidence creation and environmental monitoring.

2.6. Full-Text Level Exclusion Criteria

In the full-text evaluation phase, 217 articles were whittled out using a set of preset methodological and relevance criteria. Some of the studies were also omitted as they did not provide adequate methodological specifications in terms of techniques of analysis, sampling procedures or interpretation of the results. Others were eliminated as they only concentrated on regular monitoring of water quality but not on pollution source attribution and forensic application of investigations [36, 37]. Other exclusion criteria were studies that report the same dataset or find the same results that were previously published in previous articles. Studies that involved laboratory experiments and had not been applied in the real-life forensic water quality studies were also omitted since these experiments had no direct effect on the actual forensic water quality studies. The lack of primary data on the analysis of the reviews meant that they could not be included in the final synthesis, although background information was obtained for some of them. Following these eligibility questions, fifty-three (53) studies were finally incorporated in the final qualitative synthesis. Those studies were a variety of analytical improvements in the field of forensic water quality analysis in the form of chromatographic fingerprinting procedures, mass spectrometry with high resolutions of new contaminants, microbial source tracking methods based on DNA analysis, isotope tracing methodologies, and portable sensors.

2.7. Quality Appraisal of Included Studies

A quality appraisal of the studies included was done to make sure that the evidence synthesis is methodologically rigorous and reliable. The quality of each study was evaluated based on simplified criteria often utilised in environmental systematic reviews and concentrated on methodological transparency, analytical reliability, sampling design and usefulness to forensic water quality study [38, 39]. Evaluations of studies were determined through four criteria, namely: (i) sufficient transparency of the analytical method and instrument, (ii) sufficiency of sampling and experimental design, (iii) strength of data interpretation and source attribution, and (iv) relevance of findings to the real-life settings of forensic or environmental inquiries. Such studies, which offered extensive analytical methods, good instrumentation (e.g., mass spectrometry, molecular assays), and apparent forensic relevance, were judged to be more methodologically reliable. Articles and studies with inadequate methodological descriptions were taken with caution when synthesising. Such an appraisal procedure served to make sure that any conclusions arrived at during the review were founded on scientifically credible and methodologically sound research and that the likelihood of bias in the qualitative explanation of results was reduced.

3. Results

Table **1** summarises the literature synthesis following the PRISMA methodology. Thirteen (13) studies were synthesised, covering diverse forensic water quality applications. GC-MS fingerprinting [40] showed robust oil spill attribution, though weathering remained a limitation. DNA-based microbial source tracking [41, 42] reliably distinguished human from animal faecal inputs, with validation challenges associated with marker decay.

Table 1: Literature summary.

S. No.	Ref.	Study Type	Study Location /Region	Technique / Matrix	Sample / Study Focus	Major Findings	Forensic Relevance	Limitations / Remarks
1	[40]	Method development / Case study	Global petroleum forensic applications	GC-MS chronographic fingerprinting (oil)	Oil spill comparison	Developed integrated GC-MS fingerprinting and chemographic matching for oil identification	Foundational petroleum forensic attribution	Weathering affects fingerprints
2	[41]	Experimental / Case study	India	DNA-based MST (Bacteroidales qPCR)	Faecal pollution of surface waters	Validated host-associated markers distinguishing human vs animal sources	High-value forensic source attribution	Marker decay varies by environment
3	[43]	Review	Global	LC-MS/MS PFAS analysis + multivariate tools	PFAS contaminated sites	PFAS fingerprinting enables source apportionment	Important for industrial contamination tracing	Unknown PFAS complicate identification
4	[44]	Method development	Europe	IMS-MS rapid organic fingerprinting	Environmental samples	Demonstrated rapid screening of complex organic mixtures	Useful for forensic screening	Requires specialised instrumentation
5	[45]	Review	Europe	LC-MS/MS PFAS analysis	Biological and environmental matrices	SPE + LC-MS/MS workflow validated for PFAS detection	Trace contaminant detection for legal evidence	Rapidly evolving PFAS analytes
6	[46]	Review	Europe	Electrochemical heavy metal sensors	Field water monitoring	Portable sensors detect As, Pb, Cd	Enables rapid forensic screening	Sensor drift and calibration issues
7	[47]	Review	Europe	Portable electrochemical sensors	Trace metal field detection	Advances in modified electrodes improve detection limits	Valuable rapid screening tool	Matrix interference challenges
8	[48]	Method development	Brazil	GC-MS statistical fingerprint matching	Oil fingerprint comparison	Proposed statistical thresholds for chromatographic matching	Improves defensibility in court	Focus on unweathered samples
9	[49]	Method development	USA	HRMS non-target PFAS screening	Environmental water samples	Workflow for suspect and non-target PFAS identification	Expands forensic contaminant discovery	Computationally intensive
10	[50]	Case study	Bangladesh	Portable arsenic detection kits	Groundwater monitoring	Portable devices detect high-As contamination	Useful for rapid poisoning investigations	Requires laboratory confirmation
11	[51]	Review	Global	qPCR and digital PCR	Waterborne pathogen detection	Improved sensitivity for pathogen identification	Important for outbreak investigations	DNA presence vs viability interpretation
12	[42]	Review	Europe	Genetic MST markers	Freshwater and groundwater	Evaluates the performance of host-specific markers	Guides forensic MST implementation	Regional validation required
13	[52]	Case study	China	Pb and Sr isotopes	Soil and groundwater contamination	Isotopes distinguish natural vs anthropogenic sources	Powerful forensic tracer for metals	Requires a background geochemical database
14	[53]	Case study	Canada	GC-MS hydrocarbon fingerprinting	Oil spill case	Biomarker ratios identified the petroleum source	Strong evidence in oil spill litigation	Weathering alters ratios
15	[54]	Case study	Bulgaria	GC-MS ion chromatograms	Oil pollutants in water	SIM improved pollutant identification	Supports oil spill attribution	Needs reference samples
16	[55]	Case study	North Sea	GC-MS biomarker fingerprinting	Marine oil spills	Biomarker patterns differentiate crude oils	Widely used petroleum forensic method	Biodegradation complicates analysis
17	[56]	Case study	USA	Compound-specific isotope analysis	Weathered petroleum residues	Isotope ratios confirm oil source	Robust evidence even after weathering	High analytical cost
18	[57]	Review	Global	Petroleum biomarker analysis	Environmental oil contamination	Biomarkers provide source differentiation	Core petroleum forensic technique	Interpretation complexity
19	[58]	Case study	USA	GC-MS PAH fingerprinting	Urban sediments	PAH profiles distinguish pyrogenic vs petrogenic sources	Useful in environmental litigation	Weathering alters PAH ratios

Table 1 (Contd….)

S. No.	Ref.	Study Type	Study Location /Region	Technique / Matrix	Sample / Study Focus	Major Findings	Forensic Relevance	Limitations / Remarks
20	[59]	Case study	China	ICP-MS trace metals	Industrial wastewater contamination	Elemental signatures link contamination to industries	Important for industrial pollution attribution	Requires baseline geochemistry
21	[60]	Review	Global	ICP-MS multi-element geochemistry	Groundwater contamination	Elemental signatures distinguish natural vs anthropogenic sources	Environmental forensic geochemistry	Geological variability
22	[61]	Case study	UK	LC-MS/MS micropollutants	Wastewater effluent monitoring	Pharmaceuticals detected widely	Identifies emerging contaminants	Advanced instrumentation needed
23	[62]	Case study	USA	LC-MS/MS PFAS detection	Wastewater treatment plants	PFAS traced to industrial discharges	Important regulatory evidence	Complex mixtures
24	[63]	Case study	USA	HRMS PFAS detection	Drinking water contamination	Identified industrial PFAS contamination	Major evidence in contamination investigations	Requires expertise
25	[64]	Method development	USA	HRMS non-target screening	Environmental water	Discovery of unknown PFAS compounds	Expands forensic contaminant identification	Structural ambiguity
26	[65]	Case study	USA	GC-MS pharmaceuticals	Streams survey	Pharmaceuticals widely detected	Demonstrates anthropogenic pollution sources	Temporal variability
27	[66]	Case study	USA	LC-MS/MS emerging contaminants	Wastewater-impacted streams	Multiple pharmaceuticals identified	Pollution tracing	Complex matrices
28	[67]	Review	USA	Surfactant fingerprinting	Industrial wastewater	Surfactant profiles trace industrial sources	Useful forensic indicators	Biodegradation affects persistence
29	[68]	Case study	USA	LC-MS/MS wastewater markers	Sewage sludge	Pharmaceutical residues act as tracers	Anthropogenic contamination indicators	Sludge heterogeneity
30	[69]	Case study	Italy	Digital PCR	Urban water contamination	Improved microbial detection sensitivity	Important for outbreak tracing	Expensive instrumentation
31	[70]	Case study	Finland	RT-qPCR microbial markers	Environmental waters	RNA-based detection improves sensitivity	Enhanced microbial tracing	RNA instability
32	[71]	Case study	USA	Host-specific genetic markers	Surface water faecal contamination	HF183 marker validated	Reliable sewage indicator	Requires local calibration
33	[72]	Review	Global	MST review	Watershed contamination	Multiple MST methods validated	Important forensic microbial approach	Marker cross-reactivity
34	[73]	Method development	USA	PCR host markers	Human faecal contamination	Developed Bacteroides markers	Foundation of MST methods	Regional variability
35	[74]	Case study	Australia	qPCR sewage markers	Groundwater contamination	Sewage markers detected in aquifers	Source attribution tool	Marker persistence uncertain
36	[75]	Case study	USA	Genetic MST markers	Freshwater contamination	Validated host-associated markers	Improves source discrimination	Environmental decay
37	[76]	Review	USA	Microbial indicators	Coastal waters	Identified microbial safety markers	Public health relevance	Temporal variability
38	[77]	Case study	Brazil	Electrochemical metal sensors	Surface water monitoring	Portable detection of Pb and Cd	Rapid screening tool	Requires lab confirmation
39	[78]	Review	UK	Electrochemical arsenic detection	Drinking water analysis	Sensitive Arsenic detection	Useful field screening	Sensor drift
40	[79]	Experimental	China	Nanomaterial sensors	Heavy metal detection	Improved detection limits	Portable forensic monitoring	Matrix interference
41	[80]	Experimental	China	SERS spectroscopy	Organic pollutant detection	Ultra-trace detection possible	Rapid screening	Substrate variability

Table 1 (Contd….)

S. No.	Ref.	Study Type	Study Location /Region	Technique / Matrix	Sample / Study Focus	Major Findings	Forensic Relevance	Limitations / Remarks
42	[81]	Case study	China	SERS pesticide detection	Agricultural runoff	Rapid pesticide detection	Environmental monitoring	Quantification challenges
43	[82]	Method development	Switzerland	LC-HRMS non-target screening	Wastewater contaminants	Identified unknown micropollutants	Discovery tool	High data processing demand
44	[83]	Case study	Switzerland	HRMS suspect screening	Surface water	Detected emerging contaminants	Expanded monitoring capacity	Identification uncertainty
45	[84]	Method development	Europe	HRMS workflows	Environmental water analysis	Standard framework for unknown identification	Standardisation for HRMS forensics	Database dependency
46	[85]	Case study	USA	Advanced oxidation monitoring	Drinking water treatment	Identified trace organics	Improves water safety monitoring	Expensive technology
47	[86]	Review	USA	Chemical sewage tracers	Urban water systems	Pharmaceuticals indicate sewage input	Wastewater forensic indicator	Temporal variability
48	[87]	Case study	Switzerland	Caffeine tracer	Surface waters	Caffeine indicates domestic wastewater	Anthropogenic contamination indicator	Rapid degradation
49	[88]	Case study	USA	Pharmaceutical residues	Wastewater effluent	Drugs detected downstream of WWTPs	Pollution tracking	Incomplete removal
50	[89]	Review	UK	Emerging contaminants	Groundwater monitoring	Pharmaceuticals detected globally	Evidence of anthropogenic influence	Limited monitoring data
51	[90]	Review	Global	Environmental tracers review	Groundwater contamination	Emerging contaminants as useful tracers	Hydrochemical fingerprinting	Need standardized datasets
52	[91]	Case study	USA	Isotopic tracers	Oil and gas wastewater	Isotopes differentiate wastewater sources	Strong forensic evidence	Needs reference library
53	[92]	Case study	France	Stable isotopes	Nitrate contamination	Isotopes distinguish agricultural vs sewage sources	Important pollution attribution tool	Requires baseline data

PFAS studies [43, 45, 49] highlighted the power of LC-MS/MS and non-target HRMS for source apportionment and discovery, although with high computational and method update needs. Portable electrochemical sensors [46, 47, 50] provided rapid in-field screening for metals and arsenic, though confirmatory laboratory analysis was essential. Emerging isotope studies [52] and rapid pathogen detection [51] further reinforced the evidentiary value of advanced analytical and molecular approaches in forensic investigations.

4. Discussion

4.1. Analytical Fingerprinting for Chemical Contaminants

As part of the forensic investigation, chemical contamination of a fingerprint can be conducted through analytical fingerprinting. The analytical fingerprinting methodologies can be seen as one of the most developed and scientifically sound methods of the forensic water quality analysis. The most popular of the analysis tools include gas chromatography-mass spectrometry (GC-MS), liquid chromatography-tandem mass spectrometry (LC-MS/MS), and inductively coupled plasma mass spectrometry (ICP-MS). Highly characterized chemical signatures in polluted water bodies can be characterized using these technologies and the investigators can trace the pollutants to their source. The research papers in Table **1** show that chromatographic methods and mass spectrometric methods are still fundamental in investigations in environmental forensic especially petroleum hydrocarbons, industrial chemicals, pharmaceuticals, and emerging contaminants.

Historically, GC-MS has been at the heart of the investigation of petroleum spills as a result of its capacity to separate and identify complex mixtures of hydrocarbons. The initial efforts by Christensen *et al*. [40] developed composite GC-MS fingerprinting methods that could be used to differentiate between petroleum products in terms of chromatographic patterns and distributions of biomarkers. The analytical fingerprints help investigators to match the environment samples to the suspected source materials and this is one of the strong types of evidence that can be presented in the case of attribution of oil spill. Other studies such as Pavlova and Papazova [54] and Wang, Yang [53] adopted a similar approach and applied GC-MS ion chromatograms and ratios of biomarkers to determine petroleum sources in polluted aquatic environments. The findings of these studies emphasized that biomarker compounds such as steranes and hopanes are relatively less affected by weathering in the environment, and hence they are a good indicator of oil origin.

Rocha, Palma [48] further advanced the hydrocarbon fingerprinting technique through the introduction of statistically sound requirements regarding the matching of the GC-MS chromatography patterns in petroleum forensic studies. They showed in their work that the statistical threshold methods enhance the objectivity and defensibility of the oil spill identification in the legal environment. The stability of the biomarkers in identifying petroleum was also highlighted in earlier studies of environmental forensics. An example is provided by Gough and Rowland [55] who demonstrated that unsolved complexes of hydrocarbons give unique compositional signatures of various crude oils and Douglas, Bence [58] assess the environmental stability of petroleum hydrocarbon ratios that can be used in source attribution. Despite the fact that GC-MS fingerprinting is a potent weapon of the forensic arsenal, these analyses also admitted such limitations as the weathering, biodegradation, and photochemical transformation, which can affect chromatographic profiles with time and make the source identification more difficult.

In addition to hydrocarbon pollution, LC-MS/MS has emerged as an analysis platform to identify organic micropollution of water bodies. This is a high sensitivity and selectivity method with a wide spectrum of newly emerging pollutants, such as pharmaceuticals, personal care products, and per- and polyfluoroalkyl substances (PFAS). These findings were proven by investigations by Houtz and Sedlak [62], who found that LC-MS/MS could identify precursors of PFAS and transformation products in wastewater systems and that complex contamination pathways were linked with industrial discharges. On the same note, Kolpin, Furlong [65] undertook a massive reconnaissance of pharmaceuticals and organic wastewater contaminations in streams in the United States by chromatographic techniques which showed that anthropogenic pollutants were prevalent on the surface waters.

The fast growth of PFAS contamination studies has added more value to the significance of the sophisticated mass spectrometry in environmental forensics. According to Charbonnet, Rodowa [43], PFAS fingerprinting can be applied to locate the source of contamination to individual industries, determining patterns of unique compounds that are related to manufacturing activities. Similarly, Di Giorgi, La Maida [45] designed solid-phase workflows of extraction-LC-MS/MS to analyse PFAS in different environmental and biological samples. These specific methods of analysis enable the measurement of specific PFAS compounds with the highest level of accuracy, which helps in monitoring regulations and contamination inquiries.

The high-resolution mass spectrometry (HRMS) has also extended the power of forensic water analysis by allowing screening of unknown contaminants non-targeted. The article by Barzen-Barzen-Hanson, Roberts [64] demonstrates that by using HRMS, many new PFAS compounds have been detected in firefighting foams and contaminated groundwater, which show the potential of the non-target analysis in detecting new pollutants. On the same note, Strynar, McCord [49] suggested convenient workflows of suspect screening of PFAS in environmental samples by using HRMS. The strategies involve the combination of both sophisticated instrumentation with data analysis using computers to detect new contaminants that might not be covered by conventional targeted monitoring programs.

Elemental fingerprinting like ICP-MS has also been useful in the determination of heavy metal content in water resources, in addition to organic pollutants. ICP-MS is sensitive to trace metals at very low levels, and thus it is a potent instrument when it comes to investigations of environmental forensics. The ICP-MS analysis by Gao, Li [59] was used to estimate the pollution of drinking water reservoirs with heavy metal ions, and the authors showed that the elemental signature can identify the sources of industrial pollution. In the same regard, Reimann and de Caritat [60] indicated that it is the regional geochemical survey that is needed to differentiate between the natural geochemical background levels and anthropogenic metal contamination.

Having these strengths, there are a number of challenges. The signatures of contaminants may be modified during environmental transformation processes like weathering, dilution, microbial degradation and so on, which may complicate the forensic interpretation. Moreover, the emerging contaminants tend to be found in complex mixtures, which demand intricate analysis processes to be characterized properly. However, the combination of chromatographic fingerprinting, the use of high-resolution mass spectrometry, and the elemental analysis has contributed greatly to the capability of investigators to identify pollutants and assign the sources of contaminations during environmental forensic investigations. As the analysis in Table **1** shows, these methods of analysis are still improving and give more effective means of water resource protection and environmental litigation.

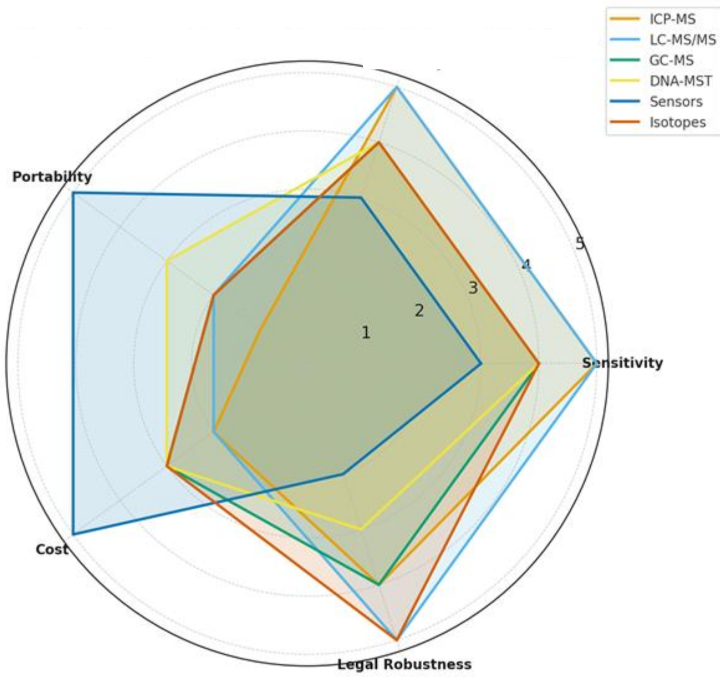

Figure 3: Comparative strengths and limitations of techniques.

Fig. (**3**) shows a radar chart comparing six major forensic water analysis techniques (ICP-MS, LC-MS/MS, GC-MS, DNA-based microbial source tracking, portable sensors and isotopic methods). Criteria assessed include sensitivity, specificity, portability, cost and legal robustness, offering a vital summary of each method's strengths and challenges in forensic applications.

4.2. Biological and Molecular Tracers

Tools in forensic water quality investigations, especially to determine the origin of microbial contamination, have grown to be biological and molecular in importance. Conventional microbial indicators including total coliforms and Escherichia coli provide a general data about faecal contamination, but cannot differentiate between human and animal sources. The limitation has been overcome by further developments in molecular biology in microbial source tracking (MST) techniques which rely on host-specific genetic markers. The methods allow the investigators to identify the source of faecal pollution in environmental waters, which can be of great help in the protection of the health of people and environmental management.

Bernhard and Field [73] carried out one of the pioneering studies in microbial source tracking when they developed host-specific genetic markers based on Bacteroides species that can be found in human faecal material. These markers were found to be very specific to human sewage and they were widely used as molecular markers of human faecal pollution in waters. This method was further developed by further studies that generated more host associated markers that could identify more animal species thus enhancing the capability in distinguishing several sources of contamination.

Ravaliya, Gentry-Shields [41] revealed the use of MST techniques in which quantitative polymerase chain reaction (qPCR) was used in monitoring faecal contamination in surface waters linked to agricultural activities. Their research confirmed the application of Bacteroidales markers to identify the source of human sewage versus livestock contamination, which demonstrates the possibility of using molecular procedures to attest to the origin of pollution. On the same note, a multi-laboratory analysis of PCR-based analyses of human faecal anaerobic bacteria was performed by Layton, Cao [71]. Their results indicated that the marker HF183 had a high specificity and sensitivity in the detection of human sewage contamination on environmental water samples.

The MST approaches have also been tested on groundwater and freshwater environments. In Ahmed, Hughes [74], they were able to detect the presence of sewage-related genetic markers in groundwater systems that were affected by the infiltration of urban wastewater. Their research has shown how the molecular methods can help in detecting the invisible routes of contamination that might not be discovered through the use of the traditional microbiological indicators. Similarly, Shanks *et al*. [75] have established qPCR assay to identify bovine faecal contamination showing that MST techniques can be used in the agricultural watershed management.

Slightly more recent technologies have also improved molecular detection technologies by adopting digital PCR and RNA-based methods of analysis. Digital PCR has a better quantification resolution, as it splits the DNA sample into thousands of separate reactions, which increases the detection limit of low-abundance microbial markers. Santoro, D'Alessio [69] used digital PCR to find microbial contaminants in urban water systems and found that the technique was more sensitive than the traditional qPCR. Moreover, Pitkänen, Ryu [70] analysed how RNA-based RT-qPCR assays are applicable to the detection of faecal bacteria in the environmental waters. Their research revealed that the markers with RNA can be a better indication of potentially metabolically active microorganisms, which could potentially give information about recent instances of contamination.

Extensive surveys have also mentioned the increased significance of MST methods in the environmental forensic field. Harwood, Staley [72] examined several microbial source tracking strategies and determined that molecular markers are effective instruments to consider in determining faecal pollution sources with the assistance of strong validation protocols. In the same manner, a comprehensive overview of host-specific genetic markers applicable in the MST was availed by Paruch and Paruch [42], highlighting their usefulness in environmental monitoring and in criminal cases.

Although there are tremendous benefits of molecular techniques, there are various limitations, which have to be taken into consideration when interpreting MST data. The environmental persistence and degradation of genetic markers is one of the primary challenges that may differ based on the conditions, e.g., temperature, sunlight, and microbial activity. The authors of the study by Ravaliya, Gentry-Shields [41] noticed that the rate of marker decay varied under varied conditions of the environment, which may affect the detection accuracy with time. Also, genetic marker cross-reactivity with other organisms can sometimes take place, which further highlights the significance of regional validation experiments prior to applying MST techniques to the forensic process.

The other restriction is that of DNA detection in the environmental samples. Detection of genetic material does not imply the presence of viable disease-causing microorganisms. Oon, Oon [51] also stressed that molecular detection techniques could identify the DNA of dead cells, which could make it difficult to determine the health risk of microorganisms. It is therefore advisable to integrate molecular methods with other complementary modalities of analysis in order to have a more detailed picture of water pollution themes.

However, with the adoption of molecular biology in the field of forensic water quality analysis, there have been great advances in the detection of the source of pollution by microbes. As has been shown in the research mentioned in Table **1**, MST methods offer a strong tool of differentiating between sewage of human origin, livestock excreta, and wildlife contamination. These strengths come in handy specifically in legal and regulatory matters where establishing the source of pollution that is being caused is crucial in environmental responsibility. As further technological growth is attained in the field of molecular diagnostics and environmental genomics, biological tracers will be increasingly used during the process of forensic water investigation.

4.3. Printable and isotopic Approaches

The current trends in the development of the environmental monitoring technologies have resulted in the invention of the portable analytical tools and isotopic tracing procedures which supplement conventional lab-based methods. They are especially useful in water quality investigations conducted in a forensic setting since they allow quickly identifying the pollutants and further evidence of pollution sources. On-site screening of water samples can be performed by portable electrochemical sensors, whereas the isotopic methods offer potent means of differentiating both natural and anthropogenic contamination.

Electrochemical sensors have received a lot of interest as instruments that can be deployed in the field and that can be used to detect traces of metals in water bodies. These types of sensors generally depend on the principle of an electrochemical reaction between modified electrodes which are selective to certain metal ions. Pujol, Evrard [46] conducted a review on the achievements of the electrochemical sensing techniques in identifying the presence of heavy metals of arsenic, lead and cadmium in water. Their research provided an insight into the benefits of portable electrochemical devices such as fast reaction time, relatively low price, and the possibility to carry out in-situ measurements without a considerable amount of sample preparation.

In electrochemical sensing, Ferrari, Carrington [47] also reported further technological developments in the form of the enhancement of portable heavy metal detection platforms based on screen-printed electrodes and nanomaterial changes. These innovations have greatly increased the detection sensitivity and selectivity making it possible to determine trace metals reliably at concentrations of interest to environmental monitoring. On the same note, Sulthana, Iqbal [50] made a thorough review of electrochemical sensors to be used in the detecting heavy metals in aqueous solutions, with a focus on their application in the rapid field screening of the environmental investigations.

Portable sensors have been used in various case studies in environmental monitoring. As an example, García-Miranda Ferrari, Foster [77] examined the electrochemical sensing systems that could be used to identify lead and cadmium in surface waters. Their results showed that portable sensors could give immediate initial measurements of contamination levels, which could also come in handy especially when there is an occurrence of pollution or during emergency management. Besides, Honeychurch [78] has shown that trace voltammetric techniques can also be used to detect lead in water by using recycled carbon electrodes, which is an indication that the creation of low-cost detection technology that can be applied in the field is a possibility.

Portable analytical devices have also been enhanced by emergent sensor technologies utilizing nanomaterials and other sophisticated spectroscopies. Liu, Huang [79] outlined electrochemical sensors made of nanomaterials that have better detection limits, and sensitivity in the trace metal analysis. Concurrently, Wang, Yang [53] investigated the application of surface-enhanced Raman spectroscopy (SERS) in detection of organic pollutants with the ultimate objective of detection at ultra-sensitivity. The method makes use of nanostructured surfaces to increase the intensity of the Raman signals so that contaminants can be detected even at very low concentrations. Another example of the use of portable spectroscopy in the response to fast environmental monitoring was provided by [81], who showed that it is possible to use smartphone-based Raman sensors to detect pesticide residues in the environment.

In spite of these benefits, there are a number of limitations associated with portable sensors that are to be taken into consideration in the forensic practice. Complex environmental samples can interfere with the matrix of the sensor, potentially causing errors in its accuracy, and the calibration drift can happen when used in the field over an extended period of time. Therefore, laboratory confirmation studies via methods, e.g., ICP-MS or LC-MS/MS are frequently needed to authenticate field data. However, portable sensors can offer important preliminary information to assist in making decisions during investigation and set up priorities during sampling during environmental incidents.

Besides portable sensing techniques, isotopic tracing techniques have become effective techniques used to establish the sources of pollution in water systems. The isotopes of elements are stable and offer a distinctive pattern of the origin and the pathways of transformation of the chemical elements in the environment. The study by Peng, Cheng [52] has shown the potential of stable isotopes in determining the sources of sulfate and nitrate pollution in the environmental system, showing that isotopic techniques can be used to distinguish between natural and man-made processes. In the same way, Widory, Petelet-Giraud [92] used coupled nitrogen and boron to trace nitrate pollution in groundwater and were able to differentiate between agricultural fertilizer input and sewage pollution.

In industrial contamination, isotopic methods have also been used. Ruhl, Dwyer [91] borrowed strontium and boron isotopes in order to describe the coal combustion residues and trace its effect on the environment. Their results indicated that isotopic signatures are some of the reliable tracers that can be used to determine the sources of contamination related to industrial operations. Isotopic compositions tend to be less susceptible to environmental weathering unlike regular chemical fingerprints; these techniques are especially useful in forensic investigations.

Isotopic analysis is further enhanced by combining the analysis with other methods of analysis to make the forensic investigations on water more convincing. As an illustration, isotopic signatures can be used in conjunction with chromatographic fingerprinting to give multiple pieces of evidence that the contaminants were caused by certain sources. This, however, needs extensive background data in terms of the geochemical variability of a region in order to interpret isotopic data effectively. In the absence of such a base information, it might be difficult to separate natural and anthropogenic sources.

In general, the portable sensing technologies and isotopic tracing techniques are significant adjunctive instruments in the contemporary forensic water quality testing. Portable sensors offer quick-on-site screening methods that can be used to respond to an investigation immediately, whereas isotopic techniques offer strong source identification by use of distinct geochemical signatures. Combined with other methods, they contribute to the capacity of environmental scientists and forensic investigators to recognize the cases of pollution, identify their perpetrators, and facilitate the implementation of the laws. These methods will increasingly become significant in securing water resources and enhancing environmental accountability as technological advances in this area have enhanced the sensitivity of analytics and their portability.

5. Conclusion

Advances in analytical techniques have transformed forensic water quality assessment from a predominantly chemical exercise into a multidisciplinary field supporting environmental justice and public health. Techniques including ICP-MS, LC-MS/MS, DNA-based microbial source tracking, isotopic fingerprinting and portable electrochemical sensors now enable ultra-trace detection, precise source attribution and timely in-field screening of both conventional and emerging pollutants. Despite notable limitations- such as calibration stability, marker decay and rapidly emerging contaminants profiles- these tools offer stronger evidentiary standards for legal processes and regulatory enforcement. Thus, by integrating laboratory precision with portable field solutions, modern techniques bridge the gap between environmental science and courtroom defensibility. Eventually, advancing forensic water analysis increases the capacity to trace pollutants, uphold accountability and safeguard communities. Sustained innovation, validation and interdisciplinary collaboration remain essential to address future challenges and ensure sustainable water governance in an era of escalating environmental threats. Ultimately, advances in forensic water analysis contribute to achieving the SDGs by improving water governance (SDG 6), safeguarding public health (SDG 3), promoting accountability in industrial practices (SDG 12), and preparing legal institutions (SDG 16). Integrating these goals into forensic practice strengthens the alignment of scientific innovation with sustainable development.

Conflict of Interest

The authors declare that there are no competing interests associated with this manuscript.

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Author Contribution

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N.B.A: Methodology, Supervision, Validation, Writing – review & editing.

I.U.K: Data curation, Validation, Writing – review & editing.

S.I: Methodology, Visualization, Writing – review & editing.

A.B.U: Conceptualization, Supervision, Writing – review & editing.

References

[1] Segato L, Mattioli W, Capello N. Water crimes within environmental crimes. In: Eman K, Meško G, Segato L, Migliorini M, Eds. Water, governance, and crime issues. Switzerland: Springer; 2020. p. 31-45. https://doi.org/10.1007/978-3-030-44798-4_3

[2] Chandra T, Sobirov B. Corporate criminal liability for illegal toxic and hazardous waste dumping. Lex Publica. 2023; 10(1): 123-40. https://doi.org/10.58829/lp.10.1.2023.123-140

[3] Ewim DRE, Orikpete OF, Scott TO, Onyebuchi CN, Onukogu AO, Uzougbo CG, *et al*. Survey of wastewater issues due to oil spills and pollution in the Niger Delta area of Nigeria: a secondary data analysis. Bull Natl Res Cent. 2023; 47(1): 116. https://doi.org/10.1186/s42269-023-01090-1

[4] Fathi-Karkan S, Easwaran EC, Kharaba Z, Rahdar A, Pandey S. Unlocking mysteries: the cutting-edge fusion of nanotechnology and forensic science. BioNanoScience. 2024; 14(3): 3572-98. https://doi.org/10.1007/s12668-024-01542-6

[5] Gould O, Nguyen N, Honeychurch KC. New applications of gas chromatography and gas chromatography-mass spectrometry for novel sample matrices in the forensic sciences: a literature review. Chemosensors. 2023; 11(10): 527. https://doi.org/10.3390/chemosensors11100527

[6] Kabir A, Holness H, Furton KG, Almirall JR. Recent advances in micro-sample preparation with forensic applications. TrAC Trends Anal Chem. 2013; 45: 264-79. https://doi.org/10.1016/j.trac.2012.11.013

[7] Estoppey N, Pfeiffer F, Glanzmann V, Reymond N, Tascon I, Huisman S, *et al*. The role of forensic science in the generation of intelligence to address environmental water contamination problems. WIREs Forensic Sci. 2023; 5(6): e1499. https://doi.org/10.1002/wfs2.1499

[8] Brčeski I, Vaseashta A. Environmental forensic tools for water resources. In: Vaseashta A, Maftei C, Eds. Water safety, security and sustainability: threat detection and mitigation. Switzerland: Springer; 2021. p. 333-70. https://doi.org/10.1007/978-3-030-76008-3_15

[9] Tsikas D. Perspectives of quantitative GC-MS, LC-MS, and ICP-MS in clinical medicine science—the role of analytical chemistry. J Clin Med. 2024; 13(23): 7276. https://doi.org/10.3390/jcm13237276

[10] Foschi M, Colantoni V, Reale S, Scappaticci C, D'Archivio AA, Biancolillo A. Analysis of volatile organic compounds in textiles: insights from GC-MS with metal content assessment using ICP-MS. Appl Sci. 2025; 15(3): 1572. https://doi.org/10.3390/app15031572

[11] Schumann J, Hlela M, Oliverio S, Bugeja L. Forensic epidemiology: bridging public health and legal investigations to address modern challenges. WIREs Forensic Sci. 2025; 7(1): e70003. https://doi.org/10.1002/wfs2.70003

[12] Holcomb DA, Stewart JR. Microbial indicators of fecal pollution: recent progress and challenges in assessing water quality. Curr Environ Health Rep. 2020; 7(3): 311-24. https://doi.org/10.1007/s40572-020-00278-1

[13] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, *et al*. Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. J Clin Epidemiol. 2021; 134: 103-12. https://doi.org/10.1016/j.jclinepi.2021.02.003

[14] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, *et al*. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021; 372: 1-9. https://doi.org/10.1136/bmj.n71

[15] Higginbotham O, O'Neill A, Barry L, Leahy A, Robinson K, O'Connor M, *et al*. The diagnostic and predictive accuracy of the PRISMA-7 screening tool for frailty in older adults: a systematic review protocol. HRB Open Res. 2020; 3: 26. https://doi.org/10.12688/hrbopenres.13042.1

[16] Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, *et al*. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann Intern Med. 2018; 169(7): 467-73. https://doi.org/10.7326/M18-0850

[17] Öner BS, Orbay M. Assessing the publication output in the field of forensic science and legal medicine using Web of Science database from 2011 to 2020. Forensic Sci Res. 2022; 7(4): 748-60. https://doi.org/10.1080/20961790.2021.2002525

[18] Issrani R, Javed F, Zeeshan HM, Yousaf F, Baig MN. Forensic science research on the Web of Science database over 22 years: a bibliometric analysis. Int J Med Toxicol Forensic Med. 2024; 14(4): e45153. https://doi.org/10.32598/ijmtfm.v14i4.45153

[19] D'Antonio M, Di Renzo V, Arienzo I, Widory D. Isotopic analysis techniques applied to forensics: new frontiers of isotope geochemistry. In: Mercurio M, Langella A, Di Maggio RM, Cappelletti P, Eds. Mineralogical analysis applied to forensics: a guidance on mineralogical techniques and their application to the forensic field. Springer; 2022. p. 251-90. https://doi.org/10.1007/978-3-031-08834-6_9

[20] Tittarelli R, Dagoli S, Cecchi R, Marsella LT, Romolo FS. 75 years of forensic profiling: a critical review. Heliyon. 2024; 10(20): e39490. https://doi.org/10.1016/j.heliyon.2024.e39490

[21] Baguma G, Bamanya G, Twinomuhwezi H, Ampaire W, Byaruhanga I, Gonzaga A, *et al*. Potentially toxic element contamination in Uganda's potable water sources: a systematic review of concentrations, health risks, and mitigation. Pollutants. 2026; 6(1): 9. https://doi.org/10.3390/pollutants6010009

[22] Farale H, Sreevidhya KB, Bathinapatla A, Kanchi S. Impact of plastic contaminants on marine ecosystems and advancement in the detection of micro/nano plastics: a review. J Hazard Mater Adv. 2025; 18: 100736. https://doi.org/10.1016/j.hazadv.2025.100736

[23] Alafer F. Emerging imaging technologies in forensic medicine: a systematic review of innovations, ethical challenges, and future directions. Diagnostics. 2025; 15(11): 1410. https://doi.org/10.3390/diagnostics15111410

[24] Hammerstrøm K, Wade A, Hanz K, Jørgensen AMK. Searching for studies. Education. 2010; 54(11-3): 1-74.

[25] Gusenbauer M, Haddaway NR. Which academic search systems are suitable for systematic reviews or meta-analyses? evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. Res Synth Methods. 2020; 11(2): 181-217. https://doi.org/10.1002/jrsm.1378

[26] Siddik AM, Varghese G, Megson D. Environmental forensic: need for comprehensive guidelines for environmental forensic investigations. Detritus. 2024; 27: I-III. https://doi.org/10.31025/2611-4135/2024.19388

[27] Gutierrez-Lopez A. Methodological guide to forensic hydrology. Water. 2022; 14(23): 3863. https://doi.org/10.3390/w14233863

[28] Jaibaji M, Najim O, Alali H, Wood L, Van Niekerk L, Bonner T, *et al*. Single-stage vs. multi-stage reconstruction in multi-ligament knee injuries: a systematic review and meta-analysis of outcomes and complications. J Clin Med. 2025; 14(19): 6897. https://doi.org/10.3390/jcm14196897

[29] August O, Sibiya M, Ilunga M, Sumbwanyambe M. Remote sensing and machine learning approaches for hydrological drought detection: a PRISMA review. Water. 2026; 18(3): 369. https://doi.org/10.3390/w18030369

[30] Dennstädt F, Zink J, Putora PM, Hastings J, Cihoric N. Title and abstract screening for literature reviews using large language models: an exploratory study in the biomedical domain. Syst Rev. 2024; 13(1): 158. https://doi.org/10.1186/s13643-024-02575-4

[31] Teo L, Van Elswyk ME, Lau CS, Shanahan CJ. Plus-abstract versus title-only first-level screening approach: a case study using a systematic review of dietary patterns and sarcopenia risk to compare screening performance. Syst Rev. 2023; 12(1): 211. https://doi.org/10.1186/s13643-023-02374-3

[32] Santa-Cruz-Mérida GV, Otomo JI, Araoz-Prado DR, Rodrigues EA, de Andrade DA, Bustillos OV. Advanced analytical approaches for phenolic compounds in groundwater: a PRISMA systematic review. Water. 2025; 17(8): 1173. https://doi.org/10.3390/w17081173

[33] Khan A, Ali S, Iqbal M. Environmental forensics: tracing pollutants and toxic substances using biological indicators in forensic investigations. Int J Appl Biol Forensic. 2026; 10(1): 254-61.

[34] Piran MJ, Tran NH. Enhancing research methodology and academic publishing: a structured framework for quality and integrity. arXiv. 2024;arXiv:2412.05683.

[35] Villa M, Le Pera M, Cassina T, Bottega M. Reporting quality of abstracts from randomised controlled trials published in leading critical care nursing journals: a methodological quality review. BMJ Open. 2023; 13(3): e070639. https://doi.org/10.1136/bmjopen-2022-070639

[36] Trifu A, Smîdu E, Badea DO, Bulboacă E, Haralambie V. Applying the PRISMA method for obtaining systematic reviews of occupational safety issues in literature search. MATEC Web Conf. 2022; 354: 1-8. https://doi.org/10.1051/matecconf/202235400052

[37] Helbach J, Hoffmann F, Pieper D, Allers K. Reporting according to the preferred reporting items for systematic reviews and meta-analyses for abstracts (PRISMA-A) depends on abstract length. J Clin Epidemiol. 2023; 154: 167-77. https://doi.org/10.1016/j.jclinepi.2022.12.019

[38] Bilotta GS, Milner AM, Boyd IL. Quality assessment tools for evidence from environmental science. Environ Evid. 2014; 3(1): 14. https://doi.org/10.1186/2047-2382-3-14

[39] Koelmans AA, Nor NHM, Hermsen E, Kooi M, Mintenig SM, De France J. Microplastics in freshwaters and drinking water: critical review and assessment of data quality. Water Res. 2019; 155: 410-22. https://doi.org/10.1016/j.watres.2019.02.054

[40] Christensen JH, Hansen AB, Tomasi G, Mortensen J, Andersen O. Integrated methodology for forensic oil spill identification. Environ Sci Technol. 2004; 38(10): 2912-8. https://doi.org/10.1021/es035261y

[41] Ravaliya K, Gentry-Shields J, Garcia S, Heredia N, Fabiszewski de Aceituno A, Bartz FE, *et al*. Use of Bacteroidales microbial source tracking to monitor fecal contamination in fresh produce production. Appl Environ Microbiol. 2014; 80(2): 612-7. https://doi.org/10.1128/AEM.02891-13

[42] Paruch L, Paruch AM. An overview of microbial source tracking using host-specific genetic markers to identify origins of fecal contamination in different water environments. Water. 2022; 14(11): 1809. https://doi.org/10.3390/w14111809

[43] Charbonnet JA, Rodowa AE, Joseph NT, Guelfo JL, Field JA, Jones GD, *et al*. Environmental source tracking of per- and polyfluoroalkyl substances within a forensic context: current and future techniques. Environ Sci Technol. 2021; 55(11): 7237-45. https://doi.org/10.1021/acs.est.0c08506

[44] Roman-Hubers AT, McDonald TJ, Baker ES, Chiu WA, Rusyn I. A comparative analysis of analytical techniques for rapid oil spill identification. Environ Toxicol Chem. 2021; 40(4): 1034-49. https://doi.org/10.1002/etc.4961

[45] Di Giorgi A, La Maida N, Taoussi O, Pichini S, Busardò FP, Tini A, *et al*. Analysis of perfluoroalkyl substances (PFAS) in conventional and unconventional matrices: clinical outcomes. J Pharm Biomed Anal Open. 2023; 1: 100002. https://doi.org/10.1016/j.jpbao.2023.100002

[46] Pujol L, Evrard D, Groenen-Serrano K, Freyssinier M, Ruffien-Cizsak A, Gros P. Electrochemical sensors and devices for heavy metals assay in water: the French groups' contribution. Front Chem. 2014; 2: 19. https://doi.org/10.3389/fchem.2014.00019

[47] Ferrari AGM, Carrington P, Rowley-Neale SJ, Banks CE. Recent advances in portable heavy metal electrochemical sensing platforms. Environ Sci Water Res Technol. 2020; 6(10): 2676-90. https://doi.org/10.1039/D0EW00407C

[48] Rocha AC, Palma C, da Silva RJB. Development and validation of statistically sound criteria for the match of unweathered GC-MS fingerprints in oil spill forensics. Chemosphere. 2022; 289: 133085. https://doi.org/10.1016/j.chemosphere.2021.133085

[49] Strynar M, McCord J, Newton S, Washington J, Barzen-Hanson K, Trier X, *et al*. Practical application guide for the discovery of novel PFAS in environmental samples using high resolution mass spectrometry. J Expo Sci Environ Epidemiol. 2023; 33(4): 575-88. https://doi.org/10.1038/s41370-023-00578-2

[50] Sulthana SF, Iqbal UM, Suseela SB, Anbazhagan R, Chinthaginjala R, Chitathuru D, *et al*. Electrochemical sensors for heavy metal ion detection in aqueous medium: a systematic review. ACS Omega. 2024; 9(24): 25493-512. https://doi.org/10.1021/acsomega.4c00933

[51] Oon YL, Oon YS, Ayaz M, Deng M, Li L, Song K. Waterborne pathogens detection technologies: advances, challenges, and future perspectives. Front Microbiol. 2023; 14: 1286923. https://doi.org/10.3389/fmicb.2023.1286923

[52] Peng J, Cheng C, Wang S, Hu G, Yan J, Yu R. Application of stable isotopes in identifying the sources and formation of sulfate and nitrate in PM2.5: a review. Atmosphere. 2024; 15(11): 1312. https://doi.org/10.3390/atmos15111312

[53] Wang Z, Yang C, Yang Z, Sun J, Hollebone B, Brown C, *et al*. Forensic fingerprinting and source identification of the 2009 Sarnia (Ontario) oil spill. J Environ Monit. 2011; 13(11): 3004-17. https://doi.org/10.1039/c1em10620a

[54] Pavlova A, Papazova D. Oil-spill identification by gas chromatography-mass spectrometry. J Chromatogr Sci. 2003; 41(5): 271-3. https://doi.org/10.1093/chromsci/41.5.271

[55] Gough MA, Rowland SJ. Characterization of unresolved complex mixtures of hydrocarbons in petroleum. Nature. 1990; 344(6267): 648-50. https://doi.org/10.1038/344648a0

[56] Reddy CM, Pearson A, Xu L, McNichol AP, Benner BA, Wise SA, *et al*. Radiocarbon as a tool to apportion the sources of polycyclic aromatic hydrocarbons and black carbon in environmental samples. Environ Sci Technol. 2002; 36(8): 1774-82. https://doi.org/10.1021/es011343f

[57] Wang Z, Stout SA. Chemical fingerprinting of spilled or discharged petroleum—methods and factors affecting petroleum fingerprints in the environment. Oil Spill Environ Forensics. 2007; 2007: 1-53. https://doi.org/10.1016/B978-012369523-9/50005-7

[58] Douglas GS, Bence AE, Prince RC, McMillen SJ, Butler EL. Environmental stability of selected petroleum hydrocarbon source and weathering ratios. Environ Sci Technol. 1996; 30(7): 2332-9. https://doi.org/10.1021/es950751e

[59] Gao B, Li Q, Zhou HD, Gao JJ, Zou XW, Huang Y. Application of ICP-MS in the health risk assessment of heavy metals for drinking water sources in reservoirs. Spectrosc Spect Anal. 2014; 34(5): 1398-402.

[60] Reimann C, de Caritat P. Distinguishing between natural and anthropogenic sources for elements in the environment: regional geochemical surveys versus enrichment factors. Sci Total Environ. 2005; 337(1-3): 91-107. https://doi.org/10.1016/j.scitotenv.2004.06.011

[61] Baker TC, Tymm FJ, Murch SJ. Assessing environmental exposure to β-N-methylamino-L-alanine (BMAA) in complex sample matrices: a comparison of the three most popular LC-MS/MS methods. Neurotox Res. 2018; 33(1): 43-54. https://doi.org/10.1007/s12640-017-9764-3

[62] Houtz EF, Sedlak DL. Oxidative conversion as a means of detecting precursors to perfluoroalkyl acids in urban runoff. Environ Sci Technol. 2012; 46(17): 9342-9. https://doi.org/10.1021/es302274g

[63] Hu T, Zhang JL. Mass-spectrometry-based lipidomics. J Sep Sci. 2018; 41(1): 351-72. https://doi.org/10.1002/jssc.201700709

[64] Barzen-Hanson KA, Roberts SC, Choyke S, Oetjen K, McAlees A, Riddell N, *et al*. Discovery of 40 classes of per- and polyfluoroalkyl substances in historical aqueous film-forming foams (AFFFs) and AFFF-impacted groundwater. Environ Sci Technol. 2017; 51(4): 2047-57. https://doi.org/10.1021/acs.est.6b05843

[65] Kolpin DW, Furlong ET, Meyer MT, Thurman EM, Zaugg SD, Barber LB, *et al*. Pharmaceuticals, hormones, and other organic wastewater contaminants in US streams, 1999–2000: a national reconnaissance. Environ Sci Technol. 2002; 36(6): 1202-11. https://doi.org/10.1021/es011055j

[66] Furlong MT, Ouyang Z, Wu S, Tamura J, Olah T, Tymiak A, *et al*. A universal surrogate peptide to enable LC-MS/MS bioanalysis of a diversity of human monoclonal antibody and human Fc-fusion protein drug candidates in pre-clinical animal studies. Biomed Chromatogr. 2012; 26(8): 1024-32. https://doi.org/10.1002/bmc.2759

[67] Field JA, Sierra-Alvarez R. Microbial degradation of chlorinated phenols. Rev Environ Sci Biotechnol. 2008; 7(3): 211-41. https://doi.org/10.1007/s11157-007-9124-5

[68] Venkatesan AK, Halden RU. Wastewater treatment plants as chemical observatories to forecast ecological and human health risks of manmade chemicals. Sci Rep. 2014; 4(1): 3731. https://doi.org/10.1038/srep03731

[69] Santoro M, D'Alessio N, Cerrone A, Lucibelli MG, Borriello G, Aloise G, *et al*. The Eurasian otter (Lutra lutra) as a potential host for rickettsial pathogens in southern Italy. PLoS One. 2017; 12(3): e0173556. https://doi.org/10.1371/journal.pone.0173556

[70] Pitkänen T, Ryu H, Elk M, Hokajärvi AM, Siponen S, Vepsäläinen A, *et al*. Detection of fecal bacteria and source tracking identifiers in environmental waters using rRNA-based RT-qPCR and rDNA-based qPCR assays. Environ Sci Technol. 2013; 47(23): 13611-20. https://doi.org/10.1021/es403489b

[71] Layton BA, Cao Y, Ebentier DL, Hanley K, Ballesté E, Brandão J, *et al*. Performance of human fecal anaerobe-associated PCR-based assays in a multi-laboratory method evaluation study. Water Res. 2013; 47(18): 6897-908. https://doi.org/10.1016/j.watres.2013.05.060

[72] Harwood VJ, Staley C, Badgley BD, Borges K, Korajkic A. Microbial source tracking markers for detection of fecal contamination in environmental waters: relationships between pathogens and human health outcomes. FEMS Microbiol Rev. 2014; 38(1): 1-40. https://doi.org/10.1111/1574-6976.12031

[73] Bernhard AE, Field KG. Identification of nonpoint sources of fecal pollution in coastal waters by using host-specific 16S ribosomal DNA genetic markers from fecal anaerobes. Appl Environ Microbiol. 2000; 66(4): 1587-94. https://doi.org/10.1128/AEM.66.4.1587-1594.2000

[74] Ahmed W, Hughes B, Harwood VJ. Current status of marker genes of Bacteroides and related taxa for identifying sewage pollution in environmental waters. Water. 2016; 8(6): 231. https://doi.org/10.3390/w8060231

[75] Shanks OC, Atikovic E, Blackwood AD, Lu J, Noble RT, Domingo JS, *et al*. Quantitative PCR for detection and enumeration of genetic markers of bovine fecal pollution. Appl Environ Microbiol. 2008; 74(3): 745-52. https://doi.org/10.1128/AEM.01843-07

[76] Boehm AB, Van De Werfhorst LC, Griffith JF, Holden PA, Jay JA, Shanks OC, *et al*. Performance of forty-one microbial source tracking methods: a twenty-seven lab evaluation study. Water Res. 2013; 47(18): 6812-28. https://doi.org/10.1016/j.watres.2012.12.046

[77] García-Miranda Ferrari A, Foster CW, Kelly PJ, Brownson DA, Banks CE. Determination of the electrochemical area of screen-printed electrochemical sensing platforms. Biosensors. 2018; 8(2): 53. https://doi.org/10.3390/bios8020053

[78] Honeychurch K. Trace voltammetric determination of lead at a recycled battery carbon rod electrode. Sensors. 2019; 19(4): 770. https://doi.org/10.3390/s19040770

[79] Liu X, Huang L, Qian K. Nanomaterial-based electrochemical sensors: mechanism, preparation, and application in biomedicine. Adv NanoBiomed Res. 2021; 1(6): 2000104. https://doi.org/10.1002/anbr.202000104

[80] Yang L, Li P, Liu H, Tang X, Liu J. A dynamic surface-enhanced Raman spectroscopy method for ultra-sensitive detection: from the wet state to the dry state. Chem Soc Rev. 2015; 44(10): 2837-48. https://doi.org/10.1039/C4CS00509K

[81] Mu T, Wang S, Li T, Wang B, Ma X, Huang B, *et al*. Detection of pesticide residues using nano-SERS chip and a smartphone-based Raman sensor. IEEE J Sel Top Quantum Electron. 2018; 25(2): 1-6. https://doi.org/10.1109/JSTQE.2018.2869638

[82] Dom I, Biré R, Hort V, Lavison-Bompard G, Nicolas M, Guérin T. Extended targeted and non-targeted strategies for the analysis of marine toxins in mussels and oysters by LC-HRMS. Toxins. 2018; 10(9): 375. https://doi.org/10.3390/toxins10090375

[83] Hollender J, Schymanski EL, Singer HP, Ferguson PL. Nontarget screening with high resolution mass spectrometry in the environment: ready to go? Environ Sci Technol. 2017; 51(20): 11505-12. https://doi.org/10.1021/acs.est.7b02184

[84] Schymanski EL, Singer HP, Slobodnik J, Ipolyi IM, Oswald P, Krauss M, *et al*. Non-target screening with high-resolution mass spectrometry: critical review using a collaborative trial on water analysis. Anal Bioanal Chem. 2015; 407(21): 6237-55. https://doi.org/10.1007/s00216-015-8681-7

[85] Snyder SA, Wert EC, Rexing DJ, Zegers RE, Drury DD. Ozone oxidation of endocrine disruptors and pharmaceuticals in surface water and wastewater. Ozone Sci Eng. 2006; 28(6): 445-60. https://doi.org/10.1080/01919510601039726

[86] Daughton CG. Real-time estimation of small-area populations with human biomarkers in sewage. Sci Total Environ. 2012; 414: 6-21. https://doi.org/10.1016/j.scitotenv.2011.11.015

[87] Buerge IJ, Poiger T, Müller MD, Buser HR. Caffeine, an anthropogenic marker for wastewater contamination of surface waters. Environ Sci Technol. 2003; 37(4): 691-700. https://doi.org/10.1021/es020125z

[88] Glassmeyer ST, Furlong ET, Kolpin DW, Cahill JD, Zaugg SD, Werner SL, *et al*. Transport of chemical and microbial compounds from known wastewater discharges: potential for use as indicators of human fecal contamination. Environ Sci Technol. 2005; 39(14): 5157-69. https://doi.org/10.1021/es048120k

[89] Lapworth D, Stuart M. The challenge of emerging groundwater contaminants. Groundw Newsl. 2012; 50: 28-31.

[90] Lapworth D, MacDonald A, Tijani M, Darling W, Gooddy D, Bonsor H, *et al*. Residence times of shallow groundwater in West Africa: implications for hydrogeology and resilience to future changes in climate. Hydrogeol J. 2013; 21(3): 673-86. https://doi.org/10.1007/s10040-012-0925-4

[91] Ruhl LS, Dwyer GS, Hsu-Kim H, Hower JC, Vengosh A. Boron and strontium isotopic characterization of coal combustion residuals: validation of new environmental tracers. Environ Sci Technol. 2014; 48(24): 14790-8. https://doi.org/10.1021/es503746v

[92] Widory D, Petelet-Giraud E, Négrel P, Ladouche B. Tracking the sources of nitrate in groundwater using coupled nitrogen and boron isotopes: a synthesis. Environ Sci Technol. 2005; 39(2): 539-48. https://doi.org/10.1021/es0493897