

Review

Automation Systems in Pb Analysis: A Review on Environmental Water and Biological Samples

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Abstract: Lead (Pb) is one of the most relevant contaminants due to its high toxicity, even at low concentrations. The growing need for research about real-time Pb analysis in the field has driven advancements in portable, sensitive, and automated analytical methodologies. These innovations are crucial for taking proactive measures against the impacts of Pb pollution on ecosystems and public health. Flow analysis techniques have proven to be very effective in automating procedures for isolating and preconcentrating Pb in surface water and biological samples. Such automation boosts sample throughput and reduces processing time and reagent consumption, aligning with the green chemistry principles by lowering costs and minimizing waste. This review covers 31 recent automated analytical methodologies employing flow analysis techniques such as FIA, SIA, MSFIA, and LOV, emphasizing the trend toward portability and miniaturization, which facilitates in-situ analysis. Additionally, this review examines the pretreatment methods and detection systems used, highlighting the analytical parameters of each technique. The methodologies discussed demonstrate the capability to process up to 55 samples per hour accurately. Limits of quantification as low as $0.014 \mu\text{g L}^{-1}$ are reported, enabling environmental monitoring that effectively detects Pb concentrations below the WHO and EPA drinking water reference values of $10 \mu\text{g L}^{-1}$ and $15 \mu\text{g L}^{-1}$, respectively.



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Keywords: lead; automation; water samples; biological samples; flow injection analysis

1. Introduction

Lead (Pb) is a notorious environmental contaminant with a well-documented history of causing harmful health effects through inhalation and ingestion. Human activities such as mining, smelting, industrial processes, waste incineration, and coal combustion have historically contributed to substantial environmental Pb emissions. Although regulatory efforts have significantly curtailed these emissions, Pb exposure remains a critical public health issue [1–3].

Even at trace concentrations, Pb is known for its toxicity, capable of inducing severe health problems such as anemia, neurological impairments, and alterations in blood enzyme activity [4,5]. Consequently, the monitoring and regulation of Pb levels in environmental water samples are of utmost importance. The World Health Organization (WHO) has established a guideline value of $10 \mu\text{g L}^{-1}$ for Pb in drinking water [6]. At the same time, the Environmental Protection Agency (EPA) recommends taking preventive measures for levels exceeding $15 \mu\text{g L}^{-1}$ [7]. However, the EPA has currently set the maximum contaminant level goal for lead in drinking water at zero, as lead is a toxic metal that can harm human health even at low exposure levels [8].

The increasing demand for real-time Pb analysis in field research has driven the development of automatic, portable, and highly sensitive analytical techniques. These innovations are vital for implementing preventive measures against the harmful effects of environmental contamination on ecosystems and human health. Accurate trace element analysis, particularly for Pb, requires meticulous sample pretreatment to ensure effective analyte extraction prior to detection [9].

In recent years, flow analysis techniques have gained prominence for determining Pb(II) in environmental water and biological samples. Integrating traditional methods with modern instrumentation enables the partial or complete automation of various conventional analytical procedures. This automation results in enhanced simplicity, increased reliability, reduced analysis time, lower consumption of samples and reagents, and minimized handling, thereby improving safety and reproducibility [10].

This review explores and discusses the latest advancements in fully and partially automated methodologies for Pb analysis across different environmental water and biological matrices. It underscores the trend toward the development of compact, portable instruments that facilitate real-time analysis, delivering timely results crucial for addressing environmental emergencies. The review aims to demonstrate the versatility and importance of flow analysis techniques in the context of automation, highlighting their role in optimizing processes and ensuring consistent, reliable outcomes in environmental and biological sample monitoring.

A comprehensive literature search was conducted using the SciFinder and Web of Science databases. This review focused on studies published between 2013 and 2024, examining automated methods for Pb analysis in environmental samples, primarily water and biological matrices. A total of 31 studies meeting the inclusion criteria were analyzed. The review emphasizes a decade of advancements in automated lead analysis, particularly in flow techniques. To ensure an up-to-date perspective, studies published up to June 2024 were also included, highlighting key contributions that have shaped the evolution of the field.

2. Automation: Flow Injection Methodologies

Automation, as discussed in this review, involves the integration of systems capable of performing sample handling, reagent delivery, reaction monitoring, and detection with minimal human intervention. Flow-based methodologies exemplify this concept using continuous or sequential sample introduction, precise control of reagent flow, and real-time data acquisition. These automated processes enhance accuracy and reproducibility, reduce operational variability, and increase throughput, making them particularly well-suited for demanding applications such as environmental monitoring and biological analysis. By minimizing manual input, these techniques streamline workflows, ensure consistent results, and enable scalable and efficient lead determination across diverse sample matrices.

Flow Injection methodologies have become essential for automating analytical processes, addressing the need to reduce human error while optimizing chemical treatments. These techniques enhance sample throughput while reducing sample and reagent usage, supporting green chemistry principles by minimizing waste generation. Among these techniques, Flow Injection Analysis (FIA) stands out for its versatility and wide adoption in environmental analyses. Its precision in fluid handling and cost-effectiveness make it a superior alternative to traditional batch methods. FIA systems, which rely on peristaltic pumps and a range of valves such as solenoid, injection, and rotary types, offer the flexibility needed for processing complex environmental samples. This adaptability ensures consistent and reproducible sample treatment, which is crucial for high-throughput environmental monitoring [11,12]. A representative schematic of this technique is shown

in Figure 1, where the studies by Muklive et al. (2022) [13] and Jassim et al. (2023) [14] employ peristaltic pumps in an FIA system as the liquid propulsion mechanism. Through injection valves, the Pb sample or standard is introduced into the carrier stream, where it subsequently reacts with a reagent in a loop-shaped tubing arrangement before proceeding to analysis and detection. Further, in Section 2.3, the most representative figures of merit from both studies will be presented.

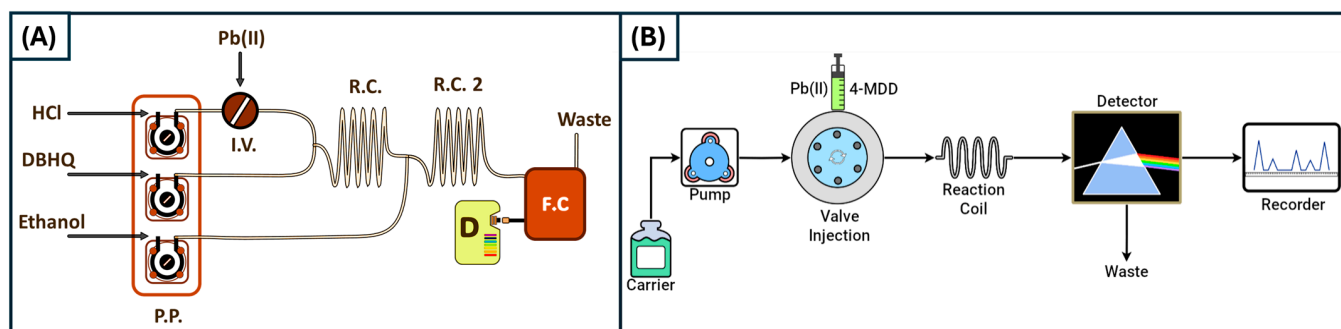


Figure 1. Schematic representations of Flow Injection Analysis (FIA) systems used for lead determination. (A) System configuration employing peristaltic pumps (P.P.), an injection valve (I.V.), and reaction coils (R.C.) for the reaction of Pb(II) with DBHQ, followed by detection (D) and flow cell (F.C.) for signal measurement [13]. (B) Alternative FIA setup using valve injection for introducing Pb(II) and reagent 4-((4methoxyphenyl)diazene)benzene-1,3-diol (4-MDD) into the carrier stream (water), which is then processed through a reaction coil (R.C.) before detection and recording [14].

Building on the advantages of FIA, Sequential Injection Analysis (SIA) offers even greater precision in handling small volumes of samples and reagents. The use of a multi-position valve (MpV) and an electric motor-driven glass syringe allows for microliter-level control, which is ideal for intricate, multiparameter analyses. Additionally, SIA's ability to minimize cross-contamination through retention coils and its compatibility with a range of detector types expands its applicability, making it suitable for highly sensitive analyses. The durability of materials like Teflon tubing and glass syringes further enhances SIA's reliability compared to systems using peristaltic pumps [15,16]. Figure 2 provides a representative schematic of an SIA system. In the automated methodologies proposed by Mitani et al. (2015) [17] and Stamna et al. (2020) [18], a syringe, acting as a piston pump, serves as the primary liquid propulsion mechanism. Different valves are used to control the flow direction of fluids, including reagents and samples.

Taking automation a step further, Multipumped Flow Systems (MPFS) employ solenoid-driven piston pumps, allowing continuous and precise liquid handling. While the system offers benefits such as easy configuration and flexibility, it requires regular maintenance due to its susceptibility to particle blockages. Nevertheless, MPFS remains a robust solution for continuous flow applications, enhancing both automation and efficiency in sample processing [19]. Figure 3 illustrates a representative application of this system, based on the work of Mattio et al. (2017) [20], where a solid-phase extraction (SPE) methodology for lead analysis is presented. In this setup, careful control of sample and reagent volumes is achieved using four small solenoid-driven piston pumps.

In this trend, Multisyringe Flow Injection Analysis (MSFIA) takes advantage of multiple syringes operating in parallel, controlled by solenoid valves, to reduce waste and conserve reagents. By combining the strengths of both FIA and SIA, MSFIA allows for greater flexibility in microanalysis. Though some limitations exist, such as slower refill times and uniform flow parameters across syringes, the method's high throughput and efficient reagent use make it an excellent choice for routine analysis [21].

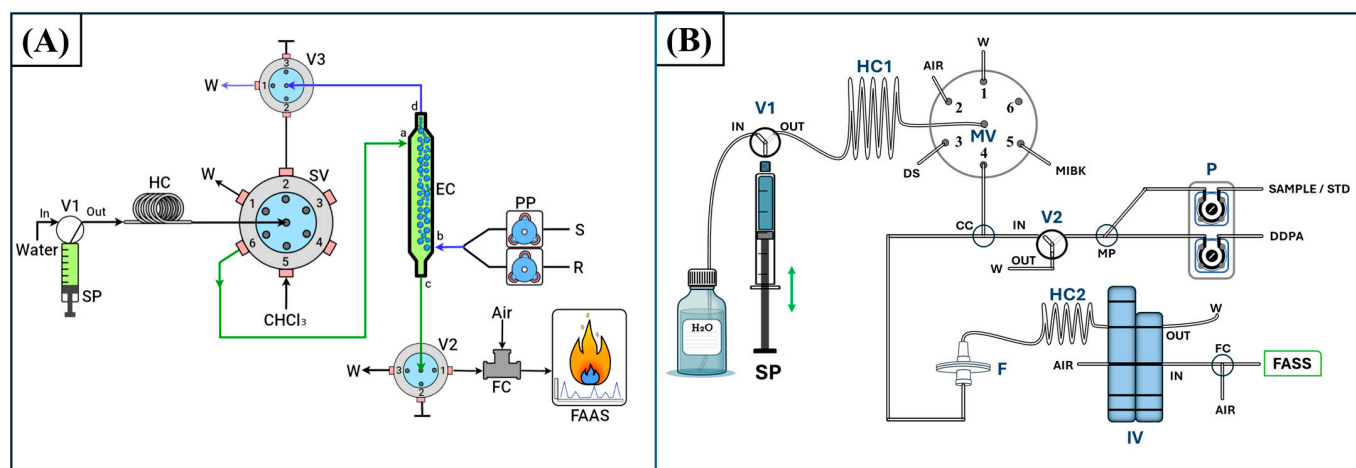


Figure 2. Schematic representation of Sequential Injection Analysis (SIA) with FAAS as lead detection system. **(A)** The system, coupled with Liquid-Liquid Microextraction (LLME) for lead determination, employs a syringe pump (SP) for liquid propulsion, along with a selection valve (SV) and two-way valves (V1, V2, V3) to control the flow of the sample (S) and reagents (R) through the holding coil (HC) for extraction. The extract is processed via the flow compensation unit (FC) before being directed for detection [17]. **(B)** An alternative setup integrates additional valves and holding coils (HC1, HC2) to enhance fluid management. This system processes either a sample or standard, using a DDPA aqueous solution and a benzophenone solution in MeOH (DS), with micro solid-phase extraction and separation prior to detection. Waste (W) is managed through the system, with holding coils HC1 and HC2 aiding the extraction process. Additional components include a filter (F), a confluence connector (CC), a mixing point (MP), and the flow compensation unit (FC) [18].

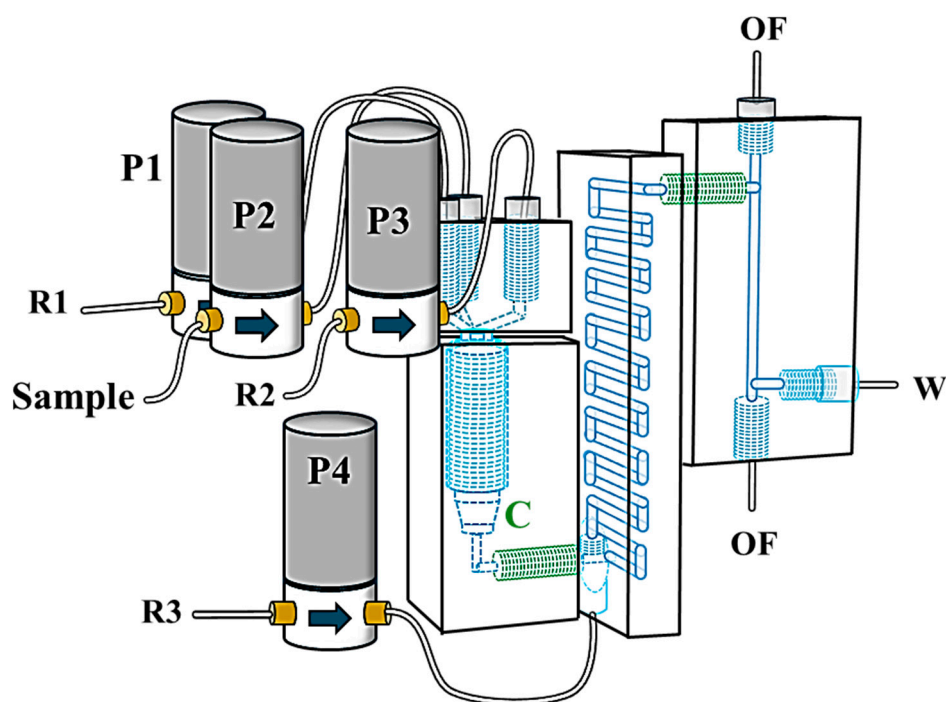


Figure 3. Schematic representation of the Multipumped Flow System (MPFS) used for lead analysis, incorporating three 3D-printed units. The system consists of four solenoid-driven piston pumps (P1, P2, P3, P4) to control the flow of the sample and reagents. The sample is introduced through R1 (nitric acid), while reagents include ammonium oxalate (R2) and PAR (R3). The resin column (C) facilitates solid-phase extraction, with optical fibers (OF) used for detection and waste (W) being managed through an outlet. Green screws and corresponding screw threads are shown to indicate the assembly of the units [20].

Innovations like Lab-On-Valve (LOV) further enhance these flow-based techniques, which incorporate microchannels and monolithic disc-shaped units for precise sample handling. The microchannels can be adapted for various procedures, including solid-phase extraction (SPE), making LOV systems ideal for complex, multi-step analyses. The integration of Sequential Injection and flow control allows for optimized reagent use, making the system efficient and highly adaptable for various analytical needs [22,23]. In this context, Beltrán et al. [4,5] developed two methodologies employing multi-commutated automatic systems. Using a multisyringe module, they performed lead analysis via SPE on a column integrated within a LOV system. These methodologies utilize detection systems such as ICP-MS and HG-AFS, highlighting the potential for full automation with on-line detection, especially in the case of ICP-MS (Figure 4). Moreover, with recent advances in 3D printing, the typical disc-shaped geometries have been modified into more functional designs adapted to the analyst's specific needs, as demonstrated by Mattio et al. (2018) [24].

Moreover, the incorporation of Lab-In-Syringe (LIS) technology has revolutionized Liquid–Liquid Microextraction (LLME), further reducing sample and reagent consumption while facilitating automation. Incorporating magnetic stirring within the syringe enhances extraction efficiency, making IS particularly useful for trace-level analysis in environmental samples. This trend toward miniaturization and efficiency is further supported by advances in 3D printing and software innovations, leading to the development of portable, on-site analytical systems. A significant contribution in this area is the work by Šrámková et al. (2018) (Figure 5), which presents a comparative study on Lab-In-Syringe with magnetic stirring. In this setup, the syringe interior is adapted to function as a mixing chamber, where a magnetic field drives the rotation of either a rod-shaped or cross-shaped stir bar. Two outlet configurations were tested: one directed upwards and the other downwards [25]. Additionally, Gonçalves Santos et al. (2022) developed a fully automated system incorporating spectrophotometric detection for lead analysis in industrial wastewater, further advancing automated on-site testing (Figure 6) [26]. As with the previous figures, the most representative figures of merit from these works will be discussed later.

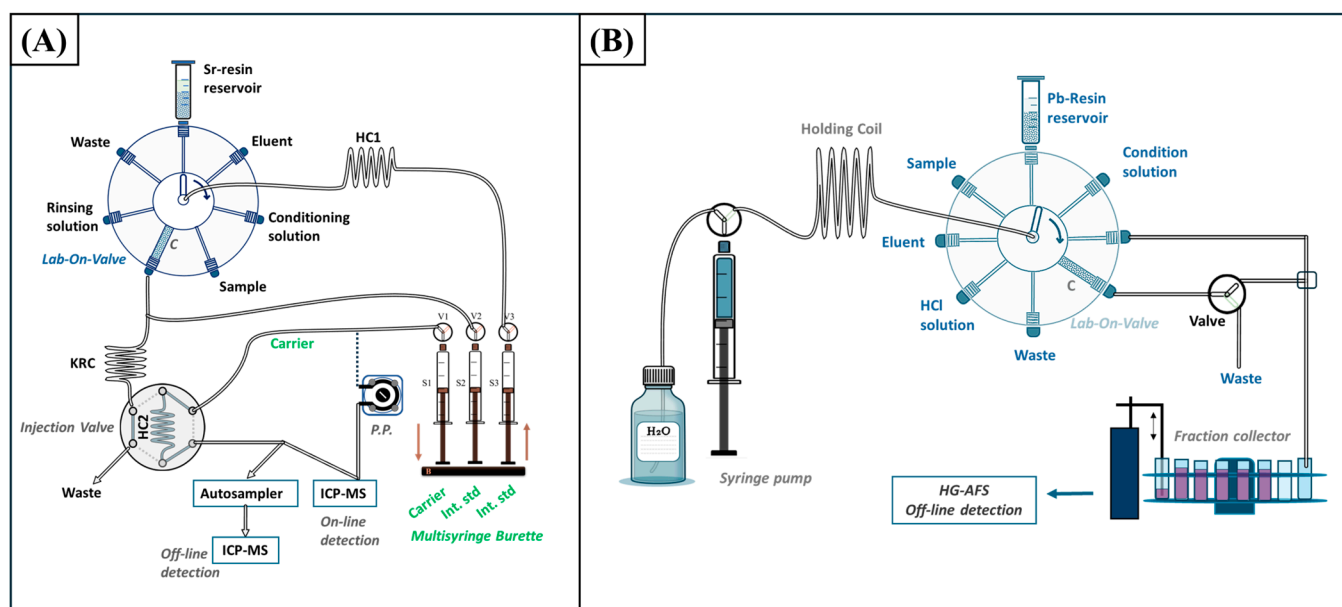


Figure 4. Cont.

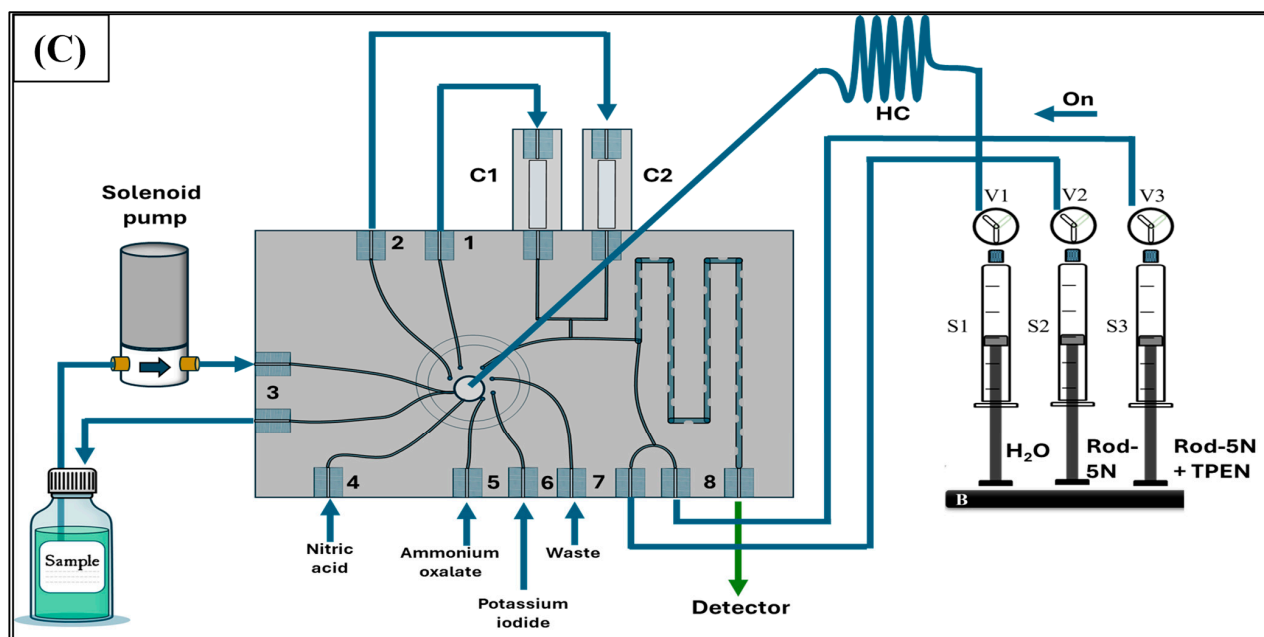


Figure 4. Schematic representations of automated lead analysis systems using Lab-On-Valve (LOV) configurations based on Beltrán et al. works [4,5] and Mattio et al. (2018) [24]. (A) System configuration for on-line detection with ICP-MS, where a multisyringe burette controls the flow of the carrier, internal standards, and reagents. The Lab-On-Valve unit is integrated with a holding coil (HC2) for sample processing [4]. (B) An alternative setup for off-line detection with HG-AFS, where the LOV system handles sample conditioning, with eluent collection in a fraction collector prior to detection. Both configurations illustrate the use of multiple syringes, solenoid valves, and automated sample handling to optimize lead analysis efficiency [5]. (C) MSFIA-LOV system used for cadmium and lead determination with C1 column for lead extraction and C2 column for cadmium; HC, holding coil [24].

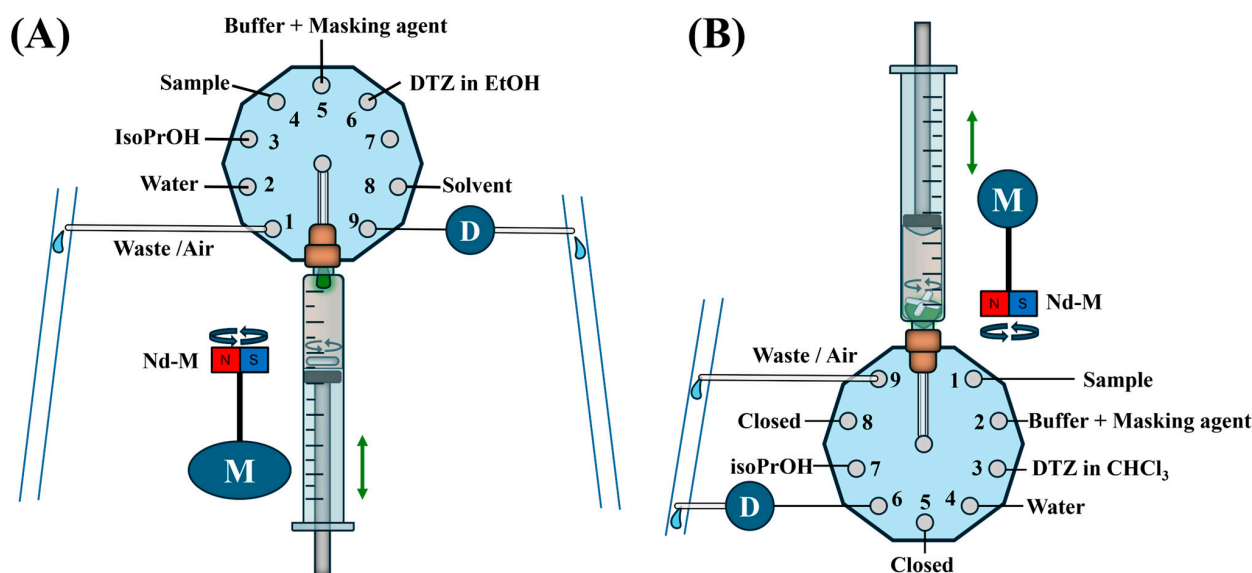


Figure 5. Lab-In-Syringe (LIS) setups with magnetic stirring by Šrámková et al. (2018) [25]. (A) System configuration for drop-in-drop microextraction (DI-SDME) into a floating drop, showing the arrangement for sample and reagent introduction through multiple ports with on-line detection (D). (B) In-drop stirring assisted DI-SDME setup, where magnetic stirring within the syringe is achieved using a DC motor (M) with neodymium magnets (Nd-M). This configuration supports precise mixing, with ports for various reagents, including dithizone (DTZ), isopropanol (isoPrOH), and buffer/masking agents, providing enhanced extraction efficiency. Tubing dimensions and port assignments facilitate controlled sample handling and waste management.

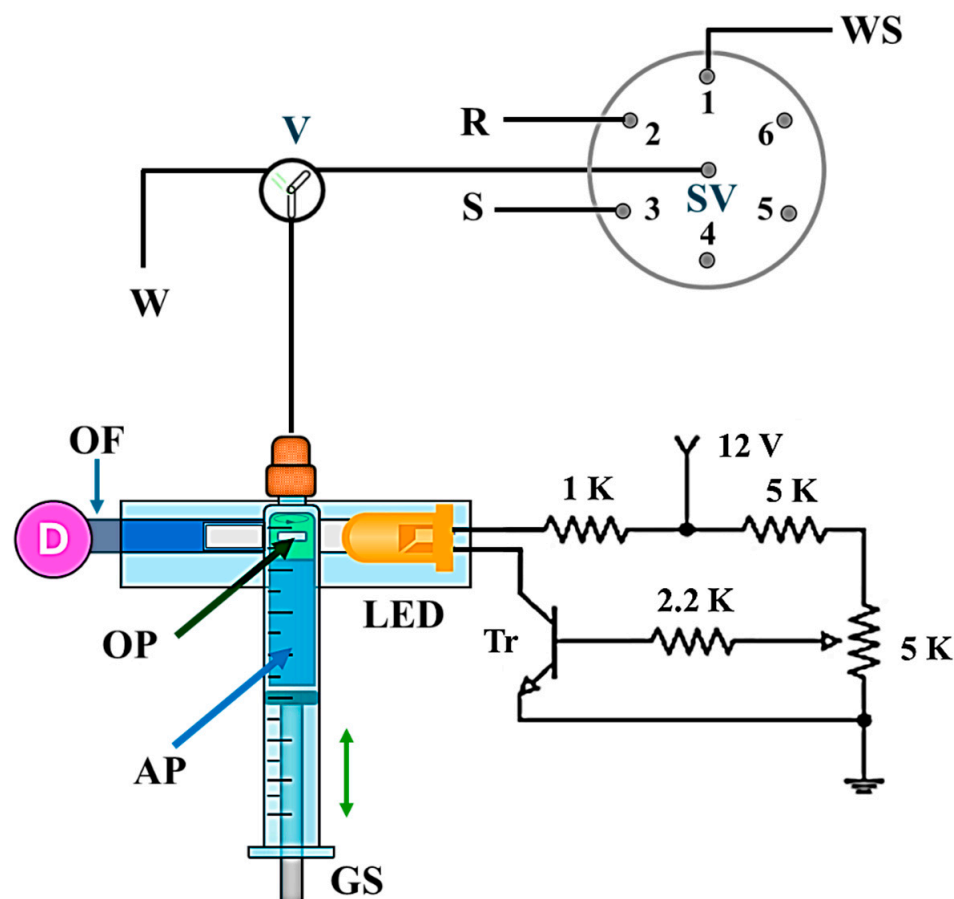


Figure 6. Schematic of the flow setup for Dispersive Liquid–Liquid Microextraction (DLLME). The system includes an eight-port selection valve (SV) to direct the sample (S), dithizone reagent (R), and washing solution (WS) through a three-way solenoid valve (V). Waste (W) is collected separately. Key components are the CCD spectrophotometric detector (D), LED: white, ultra-bright light emitting diode, optical fiber cable (OF), a 2.5 mL glass syringe (GS) for handling the organic (OP) and aqueous phases (AP). The diagram also shows fluid pathways and circuit details for automation [26].

As the demand for automation and efficiency grows, these methodologies keep evolving, setting the stage for advanced analytical applications. In the following sections, we will examine 31 studies that apply these automated techniques for Pb analysis in biological and environmental samples, particularly focusing on water samples. This exploration will highlight the analytical figures of merit for each method, classifying them based on sample pretreatment techniques (SPE, LLE), flow analytical reaction (colorimetry, voltammetry, or chemiluminescence), and sample introduction methods, with a special emphasis on chemical vapor generation techniques such as hydride generation (HG) and photochemical vapor generation (PVG). Given the number of studies discussed in this paper, only the most illustrative schematics will be included as figures, allowing readers to consult the references for further details on additional interest studies. A comparative overview of the figures of merit for the selected studies is provided in Table 1.

2.1. Solid-Phase Extraction (SPE)

SPE is a pretreatment technique where a liquid sample interacts with a solid material to selectively retain target analytes, which are then eluted for accurate quantification. This method is especially effective for detecting trace metals like lead in environmental samples, often exceeding international detection standards. In flow-based systems, the solid extractant is contained in supports ranging from simple microcolumns to advanced

3D-printed structures, which improve extraction efficiency and selectivity. Additionally, the solid phase can be automatically renewed and reused, enhancing system durability [27,28].

In this context, Sánchez Trujillo et al. (2013) developed a fully automated FIA system for trace lead analysis in environmental water samples using hydride generation-electrothermal atomic absorption spectrometry (HG-ETAAS). Two chelating resins, PSTH-CPG and TS-gel, were packed into microcolumns to evaluate their performance. Lead was retained at pH 6.0 or 8.4 and eluted with 1% hydrochloric acid. The best results were obtained with the PSTH-CPG resin, achieving a detection limit of 3.0 ng L^{-1} with an enhancement factor of 20 and a sample volume of 6.4 mL , while TS-gel showed a detection limit of 82 ng L^{-1} with an enhancement factor of 3.5. Both resins demonstrated high accuracy, with a sample throughput of 18 h^{-1} and recovery rates between 96.6% and 114% in certified reference materials (CRM), proving the system's suitability for routine lead analysis. Additionally, the fully automated nature of the system reduced human intervention, increasing precision and operational efficiency, making it well-suited for continuous environmental monitoring (Figure 7) [29].

Similarly, Yaneira Petit de Peña and Wendy Rondón (2013) developed a method for the trace determination of Pb^{2+} , Cd^{2+} , Ni^{2+} , and Co^{2+} in natural waters using minicolumns packed with 20 mg of zeolite as the solid phase. Chelates were formed with ammonium pyrrolidine dithiocarbamate (APDC) and subsequently eluted with methyl isobutyl ketone (MIBK) for detection by flame atomic absorption spectrometry (FAAS). For lead analysis, only 6 mL of sample was necessary. The method achieved detection limits as low as $0.3 \text{ } \mu\text{g L}^{-1}$, with preconcentration factors up to 201.92, and broad linear ranges from 10 to $100 \text{ } \mu\text{g L}^{-1}$ with $R^2 = 0.9993$, highlighting the high sensitivity of the system. The method demonstrated excellent recovery rates, near 100%, for metal ions in various natural water samples, proving its robustness and precision for field application. The use of zeolite minicolumns further emphasized the method's cost-effectiveness and reusability, which are critical for large-scale environmental monitoring (Figure 8) [30].

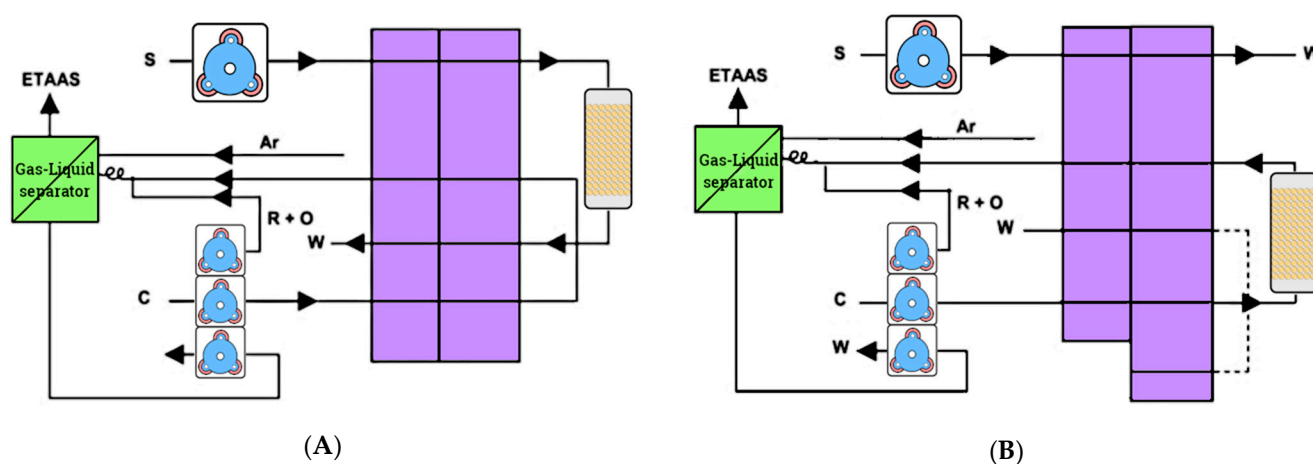


Figure 7. Schematic diagrams of the Flow Injection (FI) manifold used for the determination of lead (Pb) employing SPE. The setup includes peristaltic pumps (P1 and P2), a gas–liquid separator, and a resin column for lead preconcentration and elution. (A) Preconcentration step: the sample (S) flows through the resin while the carrier (C) and reagents (R and O) direct the process. (B) Pb elution step: lead is eluted from the resin and directed to waste (W). Additional components include oxidant (O), reductant (R), and Argon gas (Ar) for Enhanced Thermal Atomic Absorption Spectroscopy (ETAAS) detection.

Table 1. Comprehensive Chronological Overview of Analytical Figures of Merit from Reviewed Studies on Flow Injection Approaches for Lead Analysis in Water Samples.

Sample Matrix	Analyzed Elements	Flow Injection Method	Sample Pretreatment	Detection System	LOD	LOQ	Precision (RSD %)	Sample Throughput (h ⁻¹)	Reference
Natural water	Pb, Cd, Ni and Co	FIA	SPE: Zeolite A (Na-LTA, Ca-LTA) and Zeolite Y (Na-FAU, Ca-FAU)	FAAS	Na-LTA: 1.3 µg L ⁻¹ Ca-LTA: 1.7 µg L ⁻¹ Na-FAU: 0.3 µg L ⁻¹ Ca-FAU: 1.9 µg L ⁻¹	-	Na-LTA: 0.9 Ca-LTA: 1.4 Na-FAU: 0.8 Ca-FAU: 1.2	18	Yaneira Petit et al., 2013 [30]
Natural water and urine samples	Pb	SI-LAV	LLE: LPME	FAAS	1.8 µg L ⁻¹	-	2.9	7	Mitani et al., 2013 [31]
Environmental Water	Pb	FIA	SPE: PSTH-cpg and TS-gel	HG-ETAAS	3.0 ng L ⁻¹ (PSTH-cpg), 82 ng L ⁻¹ (TS-gel)	-	2.5 (PSTH-cpg) and 3.5 (TS-gel)	18	Sánchez Trujillo et al., 2013 [29]
Rain water and Airborne Particulate Filters (PM10)	Pb, Sr	MSFIA-LOV	SPE: Sr-Resin	ICP-MS	4 ng L ⁻¹	0.13 µg L ⁻¹	Repeatability: 2.2 Reproducibility: 4	5–9	Beltrán et al., 2013 [4]
Environmental water	Pb	FIA	SPE: Amberlite XAD-16 functionalized with Xylenol Orange	FAAS	1.9 µg L ⁻¹	6.3 µg L ⁻¹	3.9	30	Singh et al., 2014 [32]
River water and sediments	Pb	FIA	PVG: transition metal ion-assisted photochemical vapor generation	MC-ICPMS	0.005 ng g ⁻¹	-	<0.4	10	Gao et al., 2015 [3]
Environmental water	Pb and Cd	FIA	SPE: thiol-functionalized SBA-15	FAAS	0.22 µg L ⁻¹	-	0.4	45	Zhao et al., 2015 [33]
Environmental water	Pb	SIA	LLME	FAAS	1.5 µg L ⁻¹	-	2.7	13	Mitani et al., 2015 [17]
Environmental water, fish, and human teeth	Pb	SIA-LOV	SPE: Pb-Resin	AFS	0.004 µg L ⁻¹	0.014 µg L ⁻¹	2.4	10	Beltrán et al., 2015 [5]
Marine port waters	Pb and Cd	SIA-LOV	Colorimetric reaction using dithizone (DTZ)	UV-Vis	56 µg L ⁻¹	154 µg L ⁻¹	Repeatability: 2–5	55	Santos et al., 2015 [2]
Natural water and urine samples	Pb, Cd, Cr, and Cu	FIA	SPE: Nobias Chelate PA-1 resin	FAAS	1.6 µg L ⁻¹	-	3.3	22	Giakisikli et al., 2016 [34]
Environmental water	Pb and Cd	FIA	SPE: Disk Sorptive Extraction, using sol-gel coated fabric media	FAAS	1.8 µg L ⁻¹	-	3.1	30	Anthemidis et al., 2016 [35]

Table 1. Cont.

Sample Matrix	Analyzed Elements	Flow Injection Method	Sample Pretreatment	Detection System	LOD	LOQ	Precision (RSD %)	Sample Throughput (h ^{−1})	Reference
Tap water, phosphate fertilizer sample	Pb	SIA	Electrochemical stripping analysis	Voltammetry (SWASV)	0.5 µg L ^{−1}	1.5 µg L ^{−1}	3.1	31	Kokkinos et al., 2016 [36]
Seawater	Pb	FIA	PVG: Nickel-assisted photochemical vapor generation	ICP-MS	0.003 ng g ^{−1}	-	3.7	20	Li et al., 2017 [37]
Environmental water samples, sewage, laboratory wastewater	Pb	FIA	SPE: GO-SBA-15	SCGD-AES	0.91 µg L ^{−1}	-	3.8	6	Mo et al., 2017 [38]
Environmental water	Pb	MPFS	Colorimetric reaction using PAR	UV-Vis	2.7 µg L ^{−1}	-	5.4	4	Mattio et al., 2017 [20]
Drinking water	Pb	LIS-SDME: Method A and Method B	LLE: single-drop microextraction, colorimetric reaction with ditzone	UV-Vis	A: 75 nmol L ^{−1} B: 23 nmol L ^{−1}	A: 225 nmol L ^{−1} B: 78 nmol L ^{−1}	<5	A: 10; B: 12	Šrámková et al., 2018 [25]
Water and apple leaves	Pb	FIA	CSDF-ME	GF-AAS	0.03 µg L ^{−1}	0.1 µg L ^{−1}	2.9	30	Moinfar et al., 2018 [39]
Environmental water	Pb and Cd	MSFIA-LOV	SPE: Pb-Resin	GF-AAS	0.17 µg L ^{−1}	-	6.2	3	Mattio et al., 2018 [24]
Superficial water	Pb and Cd	FIA	SPE: with polypropylene (PP) as sorbent material and DDTC as chelating reagent.	FAAS	1.5 µg L ^{−1}	5.0 µg L ^{−1}	2.8	30	Kazantzi et al., 2019 [40]
Environmental water	Pb	SIA	SPE: DµSPE Extraction with benzophenone	FAAS	1.59 µg L ^{−1}	5.28 µg L ^{−1}	2.4	12	Stamna et al., 2020 [18]
Drinking water	Pb	MSFIA-LOV	SPE: Pb-Resin, colorimetric reaction with PAR	UV-Vis	0.79 µg L ^{−1}	2.6 µg L ^{−1}	Intraday: 3.3 Interday: 4.2	4	Rodríguez-Maese et al., 2020 [9]
Environmental water	Pb and Cr	FIA	SPE with PDPS	FAAS	1.1 µg L ^{−1}	3.8 µg L ^{−1}	<3	up to 40 h ^{−1}	Lazaridou et al., 2020 [41]
River and Industrial Effluents	Pb	FIA	SPE: O-CNTs and F-CNTs	FAAS	1.5 for O-CNTs, 1.2 for F-CNTs	5.0 for O-CNTs, 3.8 for F-CNTs	1.3% for O-CNTs, 1.2% for F-CNTs	20	Bajaj et al., 2021 [42]
Environmental water	Pb	FIA	Colorimetric reaction with DBHQ	UV-Vis	0.03 µg mL ^{−1}	0.09 µg mL ^{−1}	<1.24	51	Muklive et al., 2022 [13]

Table 1. Cont.

Sample Matrix	Analyzed Elements	Flow Injection Method	Sample Pretreatment	Detection System	LOD	LOQ	Precision (RSD %)	Sample Throughput (h ^{−1})	Reference
Industrial residual water	Pb	LIS	LLE:DLLME, colorimetric reaction with dithizone	UV-Vis	9.0 µg L ^{−1}	45.0 µg·L ^{−1}	<2	13	Gonçalves Santos et al., 2022 [26]
Biological and environmental samples, including water and soil	Pb	FIA	Colorimetric reaction with 4-MDD	UV-Vis	0.026 mg L ^{−1}	0.088 mg L ^{−1}	-	120	Jassim et al., 2023 [14]
Water, black tea, honey and rice	Pb and Cd	FIA	Electrochemical reaction	Voltammetry: DPASV with SPCE modified with C_Hal, MWCNTs and Nafion	0.20 µg L ^{−1}	3.1 µg·L ^{−1}	<5	30–40	Knihnicki et al., 2023 [43]
Seawater and urine samples	Pb, Hg, and V	FIA	SPE: MSPE with M@GO-TS	HPLC-ICP-MS	0.005 µg L ^{−1}	0.016 µg L ^{−1}	2.8	-	Montoro-Leal et al., 2023 [44]
Water samples	Pb, Cd, and Cu	LIS	LLE: LPME using NADES	FAAS	4.52 µg L ^{−1}	15 µg L ^{−1}	<3.8	15	Christoforou et al., 2024 [45]
Environmental Water	Pb	FIA	HG	AAS	0.3 µg L ^{−1}	0.9 µg L ^{−1}	0.78	25	Schlotthauer et al., 2024 [46]

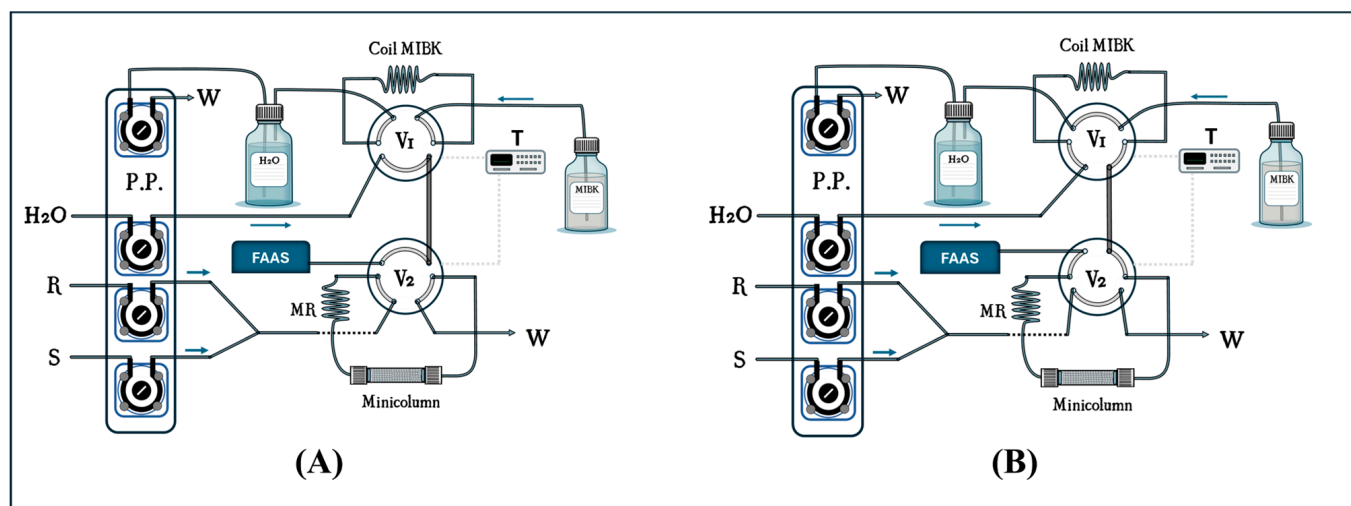


Figure 8. Flow Injection manifold for trace metal ion determination showing pre-concentration (A) and elution (B) steps. During pre-concentration, the sample (S) and APDC reagent (R) are mixed in the mixing reactor (MR) and adsorbed onto a zeolite minicolumn (V2). The coil in valve V1 is charged with MIBK. During elution, the chelate is directed to the nebulizer for detection. P.P., peristaltic pump; MIBK, methyl isobutyl ketone; FAAS, flame atomic absorption spectroscopy; W, waste.

Beltrán et al. (2013) system combined with Multisyringe Flow Injection Analysis (MSFIA) was developed for the simultaneous on-line extraction of lead and strontium, using a microcolumn packed with 35 mg of Sr-Resin, coupled with inductively coupled plasma mass spectrometry (ICP-MS). The column was conditioned with 2 mol L^{−1} HNO₃, and elution was carried out with 0.05 mol L^{−1} ammonium oxalate. The method achieved detection limits of 4 ng L^{−1} for lead and a repeatability of 2.1% RSD. This enabled the analysis of environmental samples across a wide concentration range of 0.013–50 µg L^{−1}, with $r^2 = 0.9998$. The system demonstrated high versatility, with the column being reusable for up to 160 cycles, ensuring cost efficiency. Recoveries ranged from 90% to 110% for both elements in environmental samples (rain water and airborne particulate filters), proving the method's robustness (Figure 4A) [4].

In 2015, the same group improved the system by employing atomic fluorescence spectrometry (AFS) for lead detection. The Pb-Resin (30 mg) was conditioned with 1 mol L^{−1} nitric acid, and the analyte was eluted with 1.3 mol L^{−1} glycine solution. The column could be reused up to 154 times [4]. The linear working range, expressed in mass, was 0.014–20 mg L^{−1} of Pb(II), with an $r^2 = 0.9998$, significantly enhancing sensitivity with a detection limit of 0.004 µg L^{−1} for lead. The system was validated with CRM, including bone ash and groundwater, demonstrating its applicability to both environmental and biological matrices, with excellent repeatability and robustness for long-term use (Figure 4B) [5].

Continuing the advancements in FIA systems, Singh et al. (2014) developed a fully automated FIA-FAAS system for determining Pb(II) in environmental water samples. The system utilized a two-line FIA manifold, employing 130 mg of Amberlite XAD-16 functionalized with Xylenol Orange as the solid-phase material for selective pre-concentration. This setup enabled efficient enrichment of Pb(II), which was subsequently eluted with nitric acid and detected by FAAS. The linear concentration range was 11.3–350 µg L^{−1}, with the method achieving a detection limit of 1.9 µg L^{−1} and a pre-concentration factor of 65, demonstrating its sensitivity for trace-level analysis. The system exhibited high precision, with an RSD of 3.9% at 200 µg L^{−1} Pb, indicating excellent reproducibility. Additionally, it had a throughput of 30 h^{−1}, which means that the method is capable of completing 30 analyses per hour under the optimized conditions, and the resin could be reused for up to 80 cycles, making it highly efficient for routine analysis. The method was validated with

CRM (freshwater sample), yielding recovery rates between 95 and 98%. Linearity was maintained throughout a wide concentration range, making the method reliable for detecting Pb in various environmental samples. Its automation and minimal sample handling further enhanced the system's robustness, ensuring accurate and reliable lead quantification in large-scale water analysis [32].

Further improvements were introduced by Zhao et al. (2015), who developed an FIA system that utilized mesoporous thiol-functionalized SBA-15 as the microcolumn material for preconcentrating trace amounts of Pb(II) and Cd(II) at pH 5.5, followed by sequential elution using 0.6 mol L⁻¹ HCl. Using only 60 mg of sorbent, this material offered a high surface area and exceptional selectivity for metal ion adsorption, greatly enhancing the method's sensitivity. Detection was carried out via flame atomic absorption spectrometry (FAAS), with the system displaying excellent linearity over a wide concentration range of 2–60 µg L⁻¹ ($R^2 > 0.999$). The method achieved an enhancement factor of 34 for lead, with a detection limit of 0.22 µg L⁻¹, proving highly effective for trace metal detection in complex matrices. Precision was demonstrated by consistently low RSD values, remaining below 2% at various concentration levels. The microcolumn also showed outstanding durability, retaining adsorption efficiency across more than 200 cycles without significant loss of performance, ensuring cost-effectiveness and long-term stability. With a sample throughput of 45 h⁻¹, the system was optimized for high-efficiency applications. Validation with CRM, such as tea and rice flour, yielded recovery rates between 99% and 101%, confirming the method's robustness and accuracy for both environmental and food sample analysis (Figure 9) [33].

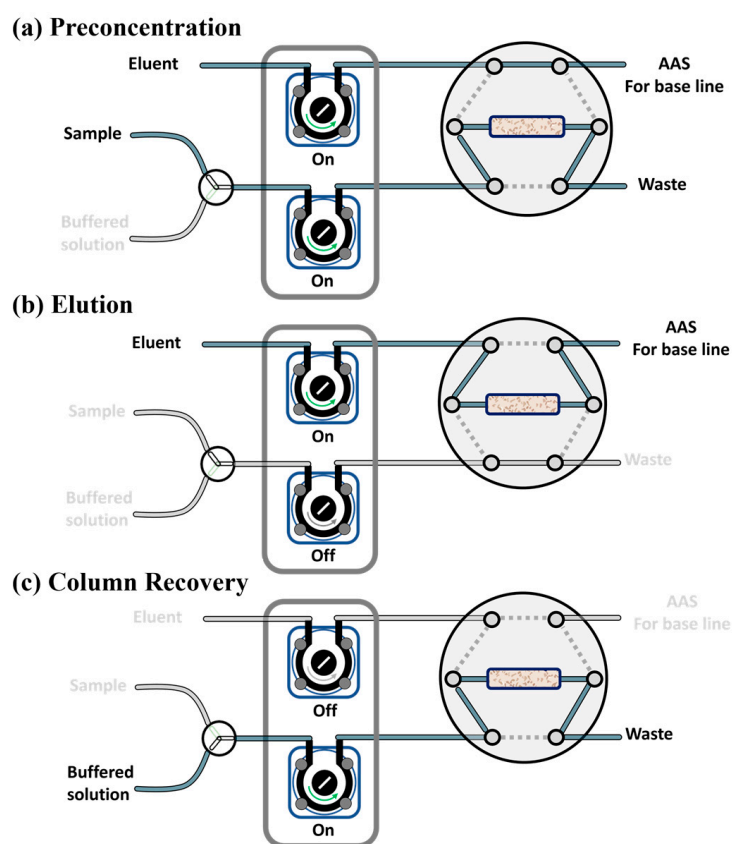


Figure 9. FIA system by Zhao et al. (2015) [33] for column-based SPE of Pb(II) with AAS detection. Mesoporous thiol-functionalized SBA-15 is used as the microcolumn material. (a) Preconcentration: sample flows through the system for baseline AAS measurement. (b) Elution: Pb(II) and Cd(II) are eluted with HCl, directing waste to W. (c) Column recovery for the next cycle.

Significant contributions in flow techniques have been made by the Laboratory of Analytical Chemistry, Aristotle University, Thessaloniki, Greece.

For instance, in 2016, Anthemidis et al. introduced a Flow Injection-fabric disk sorptive extraction (FI-FDSE) system for Pb and Cd determination in environmental water samples using FAAS (Figure 10). The study explored the effectiveness of various sol-gel coated fabric phase sorptive extraction (FPSE) media. The minicolumn was packed with a series of FPSE disks. The on-line complexation of metals with ammonium pyrrolidine dithiocarbamate (APDC) was retained on the fabric surface, and methyl isobutyl ketone (MIBK) was used to elute the analytes before atomization. The best performance was achieved with the sol-gel coated polydimethyldiphenylsiloxane (PDMDPS) medium, providing an enrichment factor of 140 and a detection limit of $1.8 \mu\text{g L}^{-1}$ for lead, with an impressive sampling frequency of 30 h^{-1} . The method demonstrated a wide linear range of $6.0\text{--}300 \mu\text{g L}^{-1}$ ($r = 0.9985$). This high throughput is particularly advantageous for routine monitoring, enabling efficient analysis of multiple samples. Key figures of merit included recoveries ranging from 94.8% to 101.0%, validated through standard reference materials and spiked samples, confirming the method's suitability for routine analysis. Its robustness and efficiency make it ideal for monitoring compliance with environmental regulations concerning heavy metal contamination [35].

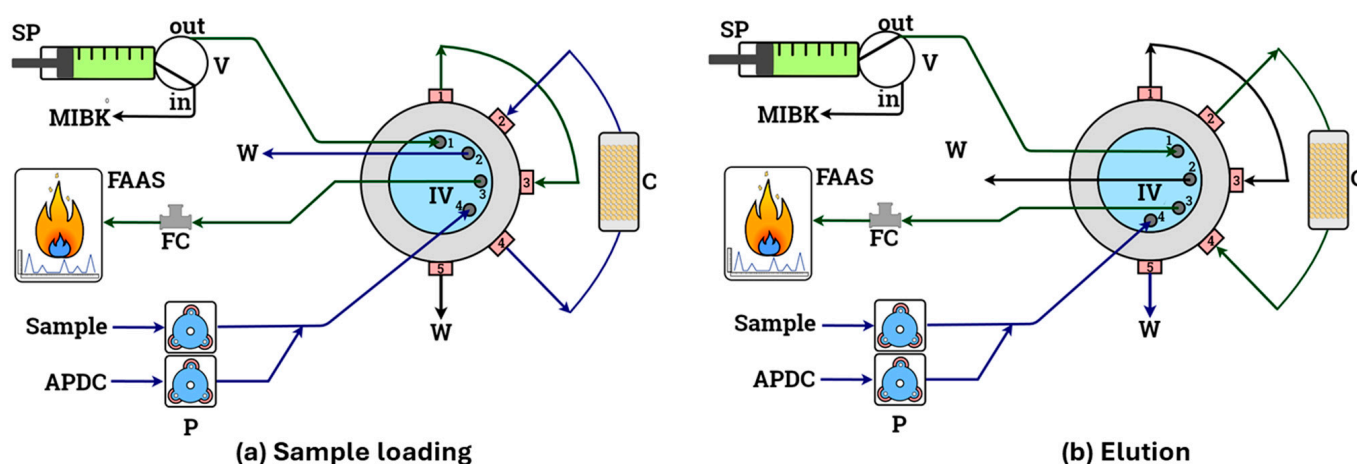


Figure 10. Method proposed by Anthemidis et al. (2016) [35]. Flow Injection-Flame Atomic Absorption Spectrometry (FI-FDSE-FAAS) manifold for Pb(II) analysis. The diagram illustrates two stages: (a) Sample Loading and (b) Elution. In the sample loading stage, the sample and ammonium pyrrolidine dithiocarbamate (APDC) are introduced into the system. In the elution stage, the methyl isobutyl ketone (MIBK) carrier transfers the analyte to the detector. Key components include SP (syringe pump), IV (injection valve), FC (flow compensation unit), P (peristaltic pump), C (FDSE minicolumn) and W (Waste).

In the same year, Giakisikli et al. developed an FI-SPE system using 40 mg of Nobias chelate PA-1 resin for the preconcentration of Cd(II), Cr(III), Cu(II), and Pb(II) from natural water and urine samples. The adsorbent exhibited strong sorption affinity for metal ions at pH levels between 5.0 and 6.0 (Figure 11). The retained analytes were effectively eluted with $1.5 \text{ mol L}^{-1} \text{ HNO}_3$. Detection was carried out using ICP-MS, enabling simultaneous multi-element analysis. The method achieved a detection limit of $1.6 \mu\text{g L}^{-1}$ for lead, with an enhancement factor of 98 and excellent precision (RSD of 3.3% at $50 \mu\text{g L}^{-1}$). The system performed reliably, with recovery rates ranging from 95% to 98.4% and a linear range of $5.5\text{--}350 \mu\text{g L}^{-1}$ for lead, confirming its robustness across different sample types. Its versatility makes it ideal for both environmental monitoring and clinical diagnostics, underscoring its broad applicability in various fields [34].

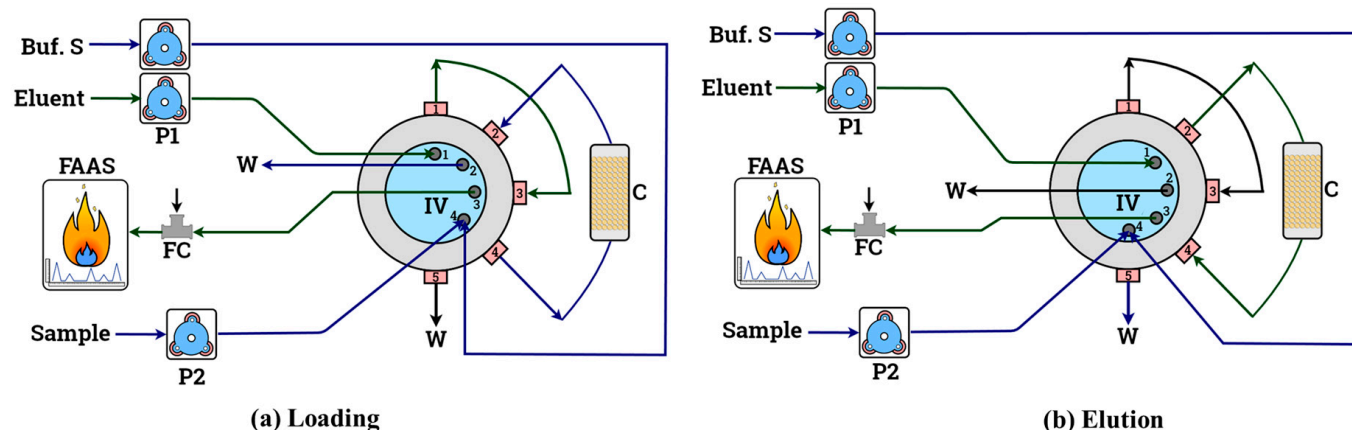


Figure 11. Schematic diagram of the manifold and operation sequence for metal determination based on the method proposed by Giakisikli et al. (2016) [34]. The system includes two stages: (a) Loading and (b) Elution. Key components are P1 and P2 (peristaltic pumps), IV (injection valve), C (minicolumn packed with resin), FC (flow compensation unit), and W (waste). The manifold uses a buffer solution (Buf. S) and an eluent solution of 1.5 M HNO₃.

In 2019, Kazantzi et al. developed an FIA system using FAAS for the automated determination of Pb(II) and Cd(II), assessing high-density polyethylene (HDPE) and polypropylene as packing materials for preconcentration columns. Each material was evaluated using 130 mg of sorbent. With dithiocarbamate (DDTC) as the chelating agent and MIBK used for elution, polypropylene demonstrated superior metal retention, achieving an enhancement factor of 180 for Pb(II) and a detection limit of 1.5 $\mu\text{g L}^{-1}$. Key performance indicators included recovery rates between 97.0% and 103.0% for environmental water samples and a linear range of 5–250 $\mu\text{g L}^{-1}$ for Pb(II) ($r = 0.9987$), showcasing the system's reliability for routine environmental monitoring and compliance testing. The optimized packing material choice significantly enhanced the overall system performance [40].

In 2020, Lazaridou et al. developed a fiber-coated sorbent extraction (FCSE) system for the automated determination of Pb(II) and Cr(VI) using FAAS. The method utilized a microcolumn packed with 200 mg of glass fiber coated with sol-gel poly(diphenylsiloxane) (sol-gel PDPS). The analytical procedure involved the on-line chelation of the target species with APDC, retention on the hydrophobic sol-gel sorbent-coated surface of the glass fibers, and subsequent elution of MIBK. For lead analysis with a preconcentration time of 120 s, the system achieved an enhancement factor of 215, a detection limit of 1.1 $\mu\text{g L}^{-1}$, and a linear range of 3.8–200 $\mu\text{g L}^{-1}$ ($r = 0.9984$). The linearity over such a wide range is a notable figure of merit, making this method particularly useful for samples with varying analyte concentrations. Recoveries ranging from 94.0% to 108.0% in natural water samples confirmed the method's accuracy for trace metal analysis. The fiber-coated sorbent material provided increased surface area for adsorption, further enhancing the method's effectiveness in detecting low levels of contaminants [41].

Continuing from previous advances, Mo et al. (2017) enhanced the sensitivity of sequential chemical glow discharge atomic emission spectrometry (SCGD-AES) by coupling it with an on-line SPE-FIA system, using 30 mg of GO-SBA-15 as the sorbent. Retention occurred at pH 5.0 using diluted HNO₃, followed by elution with the same reagent at a concentration of 0.015 mol L⁻¹. The system achieved a detection limit of 0.91 $\mu\text{g L}^{-1}$ with an enrichment factor of 15. Key performance metrics included a linear range of 10–2000 $\mu\text{g L}^{-1}$ for Pb(II) and excellent precision with an RSD of 3.8%. The method was validated with CRM (human hair and stream sediment), proving highly effective for environmental water samples, sewage, and laboratory wastewater, and the sorbent could be reused up to 55 times, highlighting its durability and sustainability for routine applications [38].

Additionally, Mattio et al. (2017) introduced a 3D-printed multipumping flow system for the determination of lead in natural waters. This system incorporated a resin column for SPE of lead, followed by spectrophotometric detection using 4-(2-pyridylazo)resorcinol (PAR) at 520 nm. The resin was conditioned with $0.05 \text{ mol L}^{-1} \text{ HNO}_3$ for lead retention, and elution was subsequently carried out using a 0.025 mol L^{-1} ammonium oxalate solution. The method displayed a linear response from 3 to $120 \text{ } \mu\text{g L}^{-1}$, with a detection limit of $2.7 \text{ } \mu\text{g L}^{-1}$ and a sampling rate of four samples per hour. Validation against ICP-AES for freshwater samples collected near anthropogenic activities confirmed the system's accuracy, with no significant differences observed at a 95% confidence level (Figure 3) [20].

One year later, the same research group developed a 3D-printed Lab-On-Valve (LOV) system for the quantification of Pb and cadmium (Cd). The system utilized 50 mg of TrisKem Pb™ Resin for lead and Amberlite® IR 120 resin for Cd, with detection performed via GF-AAS. In this method, lead analysis was carried out using the same reagents for retention and elution on the Pb-Resin. The lead analysis achieved a linear range between 0.17 and $20 \text{ } \mu\text{g L}^{-1}$, with a detection limit of $0.17 \text{ } \mu\text{g L}^{-1}$. With a sample throughput of three per hour, the method was validated against AAS, showing no significant differences. This innovative system enhanced sample mixing efficiency through its coiled section and baffles [24].

In 2020, Stamna et al. developed an automated Sequential Injection system coupled with FAAS for the detection of Pb(II) in water. The method employed a preconcentration process with solvent dispersive micro solid-phase extraction ($\text{D}\mu\text{SPE}$) using a microcolumn packed with benzophenone as the sorbent. The resin was conditioned with 0.5% ammonium diethyldithiophosphate (DDPA) in an aqueous solution, and elution was performed with methyl isobutyl ketone (MIBK). The method demonstrated a linear range of $5.28\text{--}400.0 \text{ } \mu\text{g L}^{-1}$, with a correlation coefficient of 0.9982. It achieved a detection limit of $1.59 \text{ } \mu\text{g L}^{-1}$ and an enhancement factor of 120. The system could be reused for at least 500 cycles, maintaining both accuracy and efficiency. Validation with CRM (water and mussel tissue) showed recoveries between 94.5 and 102.5%, confirming its suitability for analyzing natural water samples. Additionally, the system's flexibility enabled effective detection of Pb in various water types, including seawater and river water [18].

Later in 2020, Rodríguez-Maese et al. introduced an MSFIA-LOV fully automatic system for the detection of Pb(II), utilizing a liquid waveguide capillary cell (LWCC) for spectrophotometric detection at 520 nm. The system used 0.4 g of Pb-Resin, with Pb(II) extracted and eluted using HNO_3 at different concentrations (1 and 0.005 mol L^{-1} , respectively). The colorimetric reaction, involving 0.01% 4-(2-pyridylazo) resorcinol (PAR), was carried out automatically with assisted mechanical stirring in a mixing tank. The system achieved a detection limit of $0.79 \text{ } \mu\text{g L}^{-1}$ and a linear range of $2.6\text{--}240 \text{ } \mu\text{g L}^{-1}$ ($R^2 = 0.9967$). Additionally, the resin could be reused for up to 95 cycles without losing extraction efficiency. The method was validated using certified groundwater samples, with nearly 100% recoveries across various water matrices [9] (Figure 12).

In 2021, Bajaj et al. developed FI-SPE-FAAS systems using functionalized multi-walled carbon nanotubes (MWCNTs) for the preconcentration of Pb(II). Detection was performed using FAAS. The systems tested columns packed with 80 mg of either O-CNTs or F-CNTs. The columns were washed with $2 \text{ mol L}^{-1} \text{ HNO}_3$ and ultrapure water, and Pb(II) was eluted using $0.5 \text{ mol L}^{-1} \text{ HNO}_3$ for F-CNTs and $0.2 \text{ mol L}^{-1} \text{ HNO}_3$ for O-CNTs. The systems achieved detection limits of $1.5 \text{ } \mu\text{g L}^{-1}$ for O-CNTs and $1.2 \text{ } \mu\text{g L}^{-1}$ for F-CNTs. The method demonstrated a linear range of $5.00\text{--}160 \text{ } \mu\text{g L}^{-1}$ ($R^2 = 0.9992$) for O-CNTs and $3.80\text{--}260 \text{ } \mu\text{g L}^{-1}$ ($R^2 = 0.9996$) for F-CNTs. Validated with real water samples (river and industrial effluents), both systems showed excellent linearity and recoveries between

95.1 and 100.7%. These systems allowed to process up to 20 samples per hour, making them highly efficient for routine analyses [42].

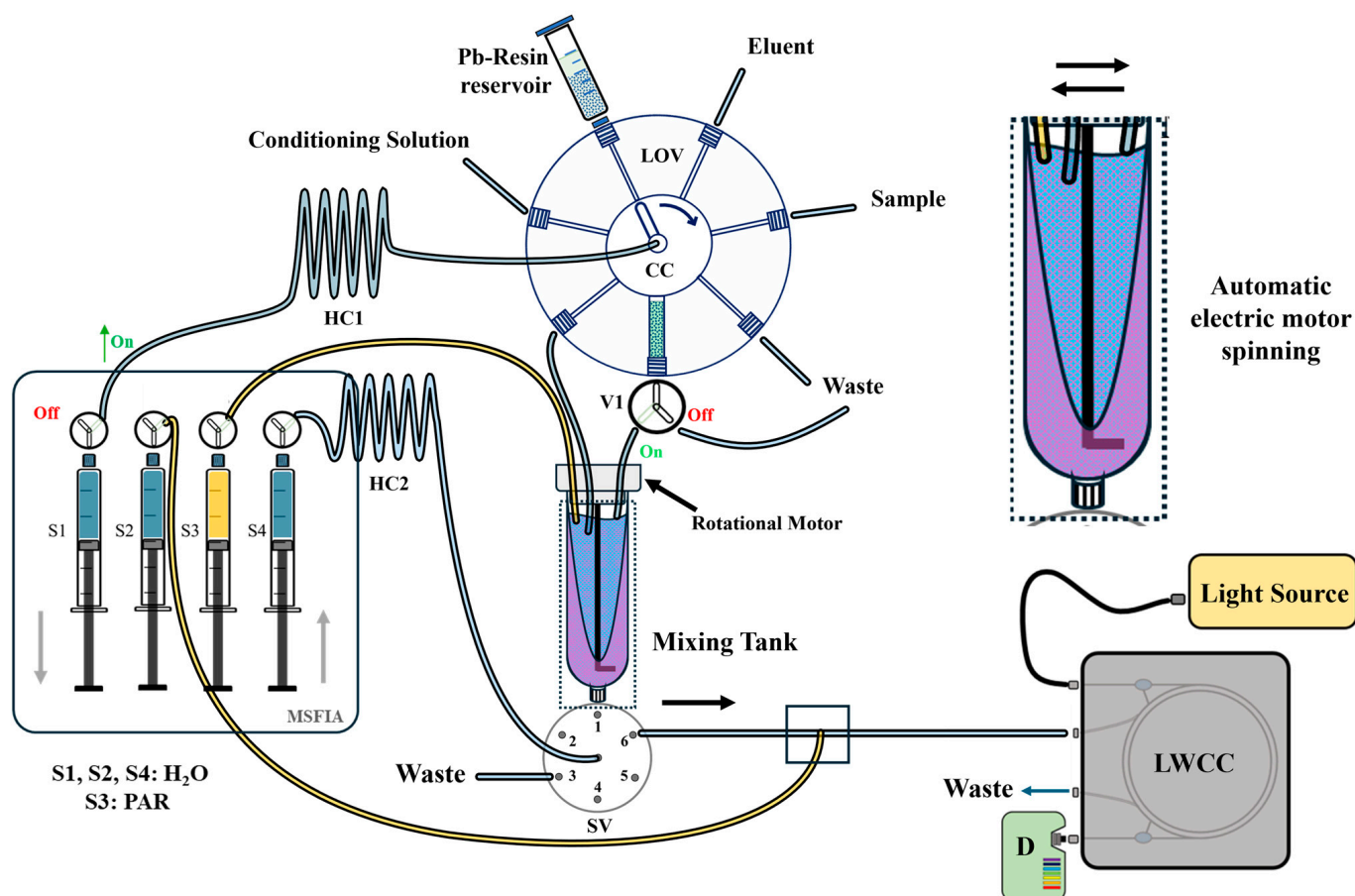


Figure 12. MSFIA-LOV system proposed by Rodríguez-Maese et al. (2020) [9] with assisted automatic stirring for Pb(II) determination. The setup includes a liquid waveguide capillary cell (LWCC), syringes (S1–S4), an external solenoid valve (V1), holding coils (HC1–2), a rotary selection valve (SV) and detector (D).

Most recently, in 2023, Montoro-Leal et al. developed an FI-MSPE system using M@GO-TS for the simultaneous preconcentration of Pb(II) and other metals. The system employed 30 mg of M@GO-TS as the sorbent, conditioned with EDTA, and eluted using 0.1 mol L^{-1} thiourea in 0.1 mol L^{-1} HCl. The method demonstrated a linear range of $0.5\text{--}20 \text{ } \mu\text{g L}^{-1}$ for Pb(II), with a correlation coefficient of $R^2 = 0.9986$. The system achieved a detection limit of 5 ng L^{-1} for Pb(II), with an enrichment factor of 27, and detection was performed using ICP-MS. Additionally, the M@GO-TS sorbent was reusable for over 200 adsorption–elution cycles, showing excellent durability and stability. The method's recoveries ranged from 90 to 112%, demonstrating its efficiency in various environmental and biological sample matrices. This performance highlights its potential as a promising approach for multi-elemental trace metal analysis in complex matrices (Figure 13) [44].

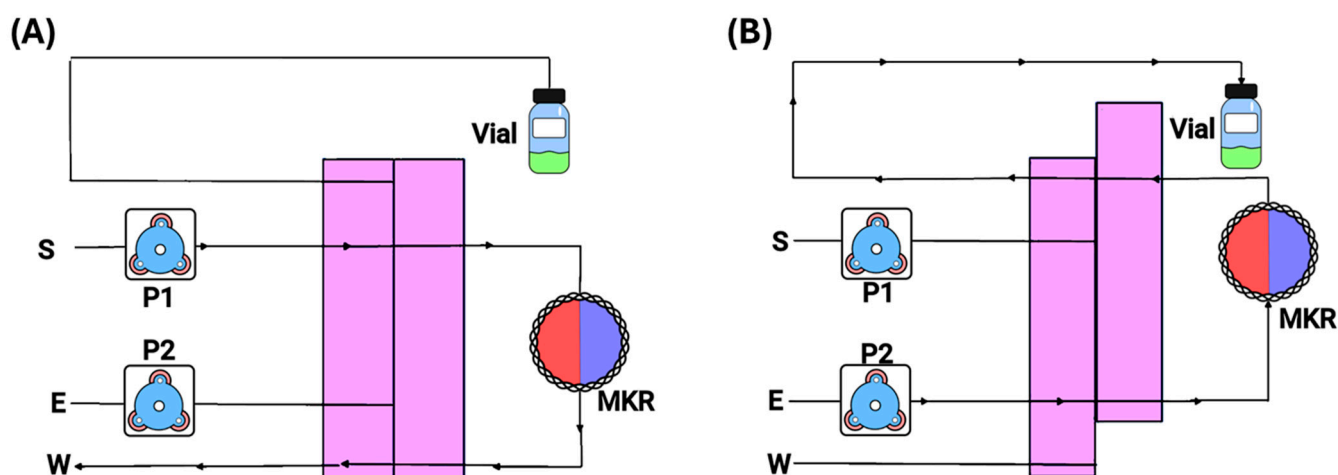


Figure 13. Schematic of the Flow Injection (FI) system used for preconcentration, as described by Montoro-Leal et al. (2023) [44]. The system includes two steps: (A) loading step and (B) elution step. Key components are peristaltic pumps (P1 and P2), a magnetic knotted reactor (MKR), waste (W), sample (S), and eluent (E).

2.2. Liquid–Liquid Extraction (LLE)

Liquid–Liquid Extraction (LLE) in flow systems is a critical sample pretreatment method used to separate and preconcentrate analytes from complex matrices, significantly enhancing detection sensitivity and accuracy. By utilizing two immiscible liquid phases, LLE facilitates continuous and automated sample processing, reducing both reagent consumption and human intervention. This efficiency makes LLE particularly valuable for trace-level analyses in environmental and biological samples. Recent advancements have shifted LLE towards miniaturized techniques, such as liquid-phase microextraction (LPME) and single-drop microextraction (SDME), which minimize solvent use and adhere to green chemistry principles. These methods are gaining popularity due to their simplicity, low cost, and adaptability to flow systems, making them ideal for automated and sensitive analyses.

Mitani et al. (2013) exploited the analytical potential of LLE by developing an automated on-line liquid-phase microextraction (LPME) method using a drop-in-plug Sequential Injection Lab-At-Valve (SI-LAV) platform for lead preconcentration and detection. Coupled with flame atomic absorption spectrometry (FAAS), this system was designed for trace-level lead determination in environmental and biological water samples. The extraction was based on forming a hydrophobic lead complex with ammonium pyrrolidine dithiocarbamate (APDC), which was extracted into an 80 μL plug of chloroform. The method achieved an enhancement factor of 125, with a detection limit of $1.8 \mu\text{g L}^{-1}$ and an RSD of 2.9% at $50.0 \mu\text{g L}^{-1}$ Pb. The system demonstrated good linearity ($r = 0.9985$) with a working range of $6.0\text{--}300 \mu\text{g L}^{-1}$ and was successfully applied to natural water and urine samples, with recoveries ranging from 94.5 to 98.0%. The method showed no statistically significant differences from CRM (water and mussel tissue) at the 95% confidence level [31].

In 2015, the same research group built on this work by developing an automatic Sequential Injection Countercurrent Liquid–Liquid Microextraction (SI-CC-LLME) system, also coupled with FAAS for Pb(II) determination. The system featured a newly designed microextraction chamber that facilitated the countercurrent flow of aqueous and organic phases. Using 120 μL of chloroform as the extractant, an enhancement factor of 130 was achieved, along with a detection limit of $1.5 \mu\text{g L}^{-1}$ and an RSD of 2.7% at $40.0 \mu\text{g L}^{-1}$ Pb. The method exhibited a good linear range ($5.0\text{--}280 \mu\text{g L}^{-1}$, $r = 0.9987$) and was validated through the analysis of CRM and environmental water samples. Recoveries ranged from

95.0% to 102.4%, confirming the method's applicability to coastal seawater and ditchwater samples [17].

In 2018, Šrámková et al. introduced two operational modes for Lab-In-Syringe automation of direct-immersion single-drop microextraction (SDME) for lead determination in drinking water. Dithizone was used as the complexing reagent, and the extractions were carried out either using a floating drop of a toluene-hexanol mixture (Method A) or a denser-than-water drop of chloroform (Method B). Method A achieved a limit of detection of 75 nmol L^{-1} , while Method B reached a lower limit of detection (LOD) of 23 nmol L^{-1} , meeting European Union water quality standards. Method B demonstrated faster extraction (150 s) compared to Method A (300 s), allowing for a higher analysis frequency of 12 samples per hour. Both methods exhibited excellent repeatability, with RSD values below 5%, and quantitative recoveries for lead in real matrices such as well and tap water. Recovery values ranged from 92.2 to 115.9% for Method A and from 93.4 to 107.3% for Method B. Detection was performed using a fiber-optic spectrophotometric system with a 1 cm optical path length, enhancing sensitivity for on-site detection (Figure 5) [25].

In the same year, Moinfar et al. (2018) developed a continuous sample drop flow microextraction (CSDF-ME) method coupled with off-line graphite furnace atomic absorption spectrometry (GF-AAS) for lead detection in water and plant samples. The technique used a peristaltic pump to introduce the sample as droplets, forming a Pb-APDC complex, which was extracted into a carbon disulfide solvent. This method provided an enrichment factor of 93, with an RSD of 2.9% at $1.0 \text{ } \mu\text{g L}^{-1}$ Pb. The calibration curve was linear in the range of $0.1\text{--}6.0 \text{ } \mu\text{g L}^{-1}$ ($r^2 = 0.995$), with detection and quantification limits of 0.03 and $0.1 \text{ } \mu\text{g L}^{-1}$, respectively. Recoveries for Pb in tap water, mineral water, and apple leaves (Standard Reference Material 1515) were 98, 100, and 94%, respectively, highlighting the method's applicability to both environmental and biological samples [39].

Gonçalves Santos et al. (2022) proposed a novel Lab-In-Syringe flow system utilizing Dispersive Liquid-Liquid Microextraction (DLLME) with a solvent lighter than water for the spectrophotometric determination of lead in industrial residues. Xylene was used as an environmentally friendly solvent alternative, complying with Green Analytical Chemistry principles. This fully automated system performed the entire process within the syringe, reducing contamination risks and improving efficiency. The method displayed high precision, with RSD values below 2.0%, and achieved detection and quantitation limits of $9.0 \text{ } \mu\text{g L}^{-1}$ and $45.0 \text{ } \mu\text{g L}^{-1}$, respectively, over a dynamic range of $50.0\text{--}250 \text{ } \mu\text{g L}^{-1}$ Pb(II) ($r = 0.9945$). With an enrichment factor of 36 and a throughput of 13 samples per hour, the system proved effective for industrial water analysis (Figure 6) [26].

In 2024, Christoforou et al. introduced a computer-controlled flow-batch Lab-In-Syringe (LIS) (Figure 14) platform for liquid-phase microextraction (LPME) using natural deep eutectic solvents (NADES) as green alternatives to conventional solvents. The system applied for the FAAS determination of Cd, Cu, and Pb in water samples achieved a linear range for Pb of $15.0\text{--}800 \text{ } \mu\text{g L}^{-1}$ ($r > 0.9986$), with a detection limit of $4.52 \text{ } \mu\text{g L}^{-1}$ and an enhancement factor of 55. Recovery values approached 100% in spiked mineral water samples, and the method's precision ($\text{RSD} \leq 3.8\%$) further underscored its reliability. Validated with certified reference materials, the method exhibited no statistically significant differences at the 95% confidence level. This platform holds potential for broader applications in environmental water analysis, with demonstrated green chemistry benefits as assessed by the Green Analytical Procedure Index (GAPI and AGREE Score, Table 2) [45].

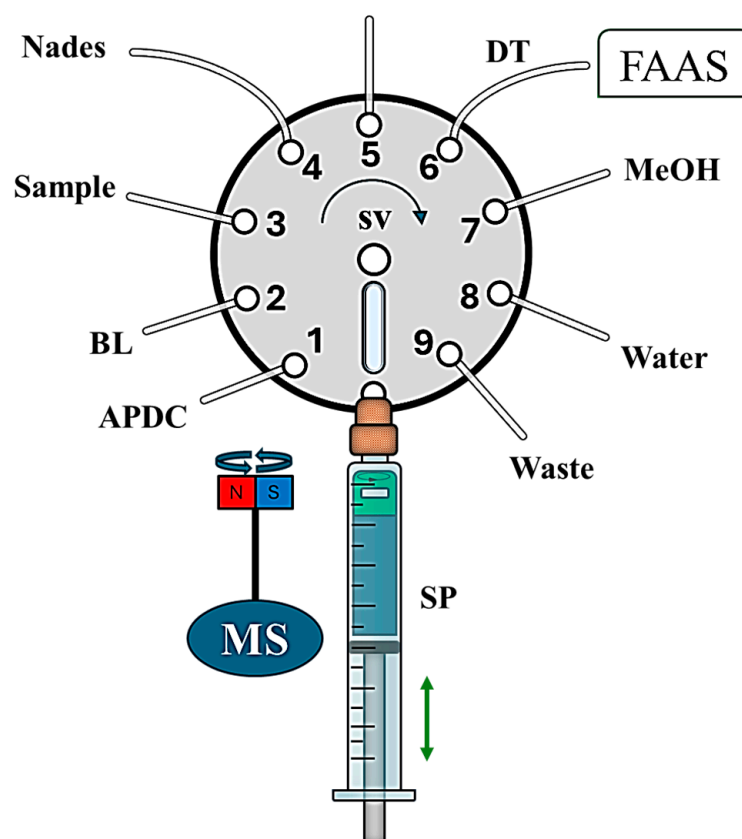


Figure 14. Schematic illustration of the LIS-LPME-FAAS system described by Christoforou et al. (2024) [45]. The system includes a selection valve (SV) that directs various solutions: natural deep eutectic solvents (NADES), delivery tube (DT), sample, blank solution (BL), ammonium pyrrolidine dithiocarbamate (APDC), methanol (MeOH), and water. The syringe pump (SP) enables liquid flow, while a magnetic stirrer (MS) enhances mixing within the syringe chamber. Detection is performed via Flame Atomic Absorption Spectroscopy (FAAS).

2.3. Flow Analytical Reaction

Flow analytical reactions utilize the precision and automation of flow-based techniques to perform critical analytical processes, including colorimetric and electrochemical analyses. In these systems, reagents and samples are accurately delivered, mixed, and allowed to react within a controlled flow environment, which minimizes human error and ensures optimal reaction conditions [47,48].

Colorimetric reactions rely on measurements of color changes in real-time, which are directly proportional to the concentration of the analyte, allowing for continuous monitoring and high-throughput analyses.

One notable example is the work by Santos et al. (2015) [2], who developed a Sequential Injection Lab-On-Valve (μ SI-LOV) system for the simultaneous screening of Cd and Pb in water samples. The method utilized dithizone as a spectrophotometric reagent, forming colored complexes with Cd at pH 12 and Pb at pH 8. The detection was performed at 550 nm, achieving limits of detection (LOD) of $34 \mu\text{g L}^{-1}$ for Cd and $56 \mu\text{g L}^{-1}$ for lead, with a sample consumption of $20 \mu\text{L}$ per assay and a throughput of 55 samples per hour. The method demonstrated accuracy comparable to flame atomic absorption spectrometry (FAAS) and was applied to marine port waters.

In a similar study, Muklive et al. (2022) [13] developed a Flow Injection chromatography method for the trace determination of lead using a colorimetric reaction between lead and 5,7-dibromo-8-hydroxyquinoline (DBHQ) in the presence of hydrochloric acid and ethanol. The complex was measured at 390 nm, with a linear range of $0.01\text{--}100 \mu\text{g mL}^{-1}$.

($r = 0.999$), an LOD of $0.03 \mu\text{g mL}^{-1}$, and a throughput of 51 samples per hour. The method yielded recoveries of around 100% for water samples, with no significant differences compared to FAAS.

Jassim et al. (2023) [14] advanced the field by designing an injection valve for a streamlined Flow Injection Analysis (FIA) system aimed at the spectrophotometric determination of Pb(II) ions using 4-((4 methoxyphenyl)diazenyl)benzene-1,3-diol at 498 nm. The system demonstrated a linear range of $0.5\text{--}27 \text{ mg L}^{-1}$ ($r = 0.9995$), with limit LOD and limit of quantification (LOQ) values of 0.026 mg L^{-1} and 0.088 mg L^{-1} , respectively. The method was successfully applied to environmental and agricultural samples, including soil and vegetable matrices, and showed recoveries between 96.67 and 100.4%.

These studies demonstrate the versatility and efficiency of flow-based colorimetric systems, particularly when combined with sample pretreatment techniques such as SPE and Liquid–Liquid Extraction (LLE), enabling highly accurate determinations of trace metals in complex matrices. Examples of this are the previously cited works by Mattio et al. (2017 and 2018) [20,24], Šrámková et al. (2018) [25], Rodríguez-Maese et al. (2020) [9], and Gonçalves Santos et al. (2022) [26].

On the other hand, electrochemical methods are highly effective in determining analyte concentrations by measuring the electrical properties of electrochemical cells, such as current, potential, and resistance. These methods often involve electron transfer at the interface between a solid electrode and a liquid electrolyte, where oxidation or reduction reactions occur. One widely used technique for trace lead determination is electrochemical stripping analysis, which involves preconcentration of Pb(II) ions onto an electrode surface, followed by a stripping step where the analyte is oxidized and detected based on the resulting current or transition time.

Kokkinos et al. (2016) developed a Sequential Injection/stripping analysis method for trace Pb(II) determination using injection-molded electrochemical fluidic cells. Carbon fiber-loaded polystyrene electrodes were integrated into the cells, which were incorporated into a home-built Sequential Injection Analysis (SIA) manifold. The method achieved a LOD of $0.5 \mu\text{g L}^{-1}$ and LOQ of $1.5 \mu\text{g L}^{-1}$, with within-cell and between-cell RSD of 3.1 and 8.9%, respectively, for $25 \mu\text{g L}^{-1}$ Pb(II). The preconcentration/stripping/cleaning cycle lasted 114 s, allowing for 31 measurements per hour. The method was successfully applied to tap water and phosphate fertilizer samples, demonstrating satisfactory agreement with electrothermal atomic absorption spectrometry (Et-AAS) (Figure 15) [36].

Recently, Knihnicki et al. (2023) introduced a Flow Injection Analysis (FIA) system equipped with a 3D-printed Direct Injection Detector (DID) for simultaneous determination of Cd and Pb in water and food samples, using only $28 \mu\text{L}$ of sample. The key component of the system, the reaction chamber, operates in a stopped-flow mode to enhance signal stability. For voltammetric detection, screen-printed carbon electrodes (SPCEs) modified with carbonized halloysite (C_Hal) and multi-walled carbon nanotubes (MWCNTs) were employed. The method involved preconcentration of both analytes on the electrode followed by signal detection. For lead, the sensor exhibited a linear response from 15 to 3000 nmol L^{-1} , with an LOD of 0.97 nmol L^{-1} (0.20 ng mL^{-1}) and an LOQ of 3.2 nmol L^{-1} . Reproducibility across five independently prepared sensors yielded an RSD of less than 5.0%, while repeatability over five calibration sets with the same sensor showed an RSD of 1.9%. Operational stability over 30 measurements showed a current decrease of only 4.0% for lead. The method demonstrated high recovery rates (96.1–102.8%) in tap, well, and mineral waters, as well as in food samples, with a precision error of less than 5.5% (Figure 16) [43].

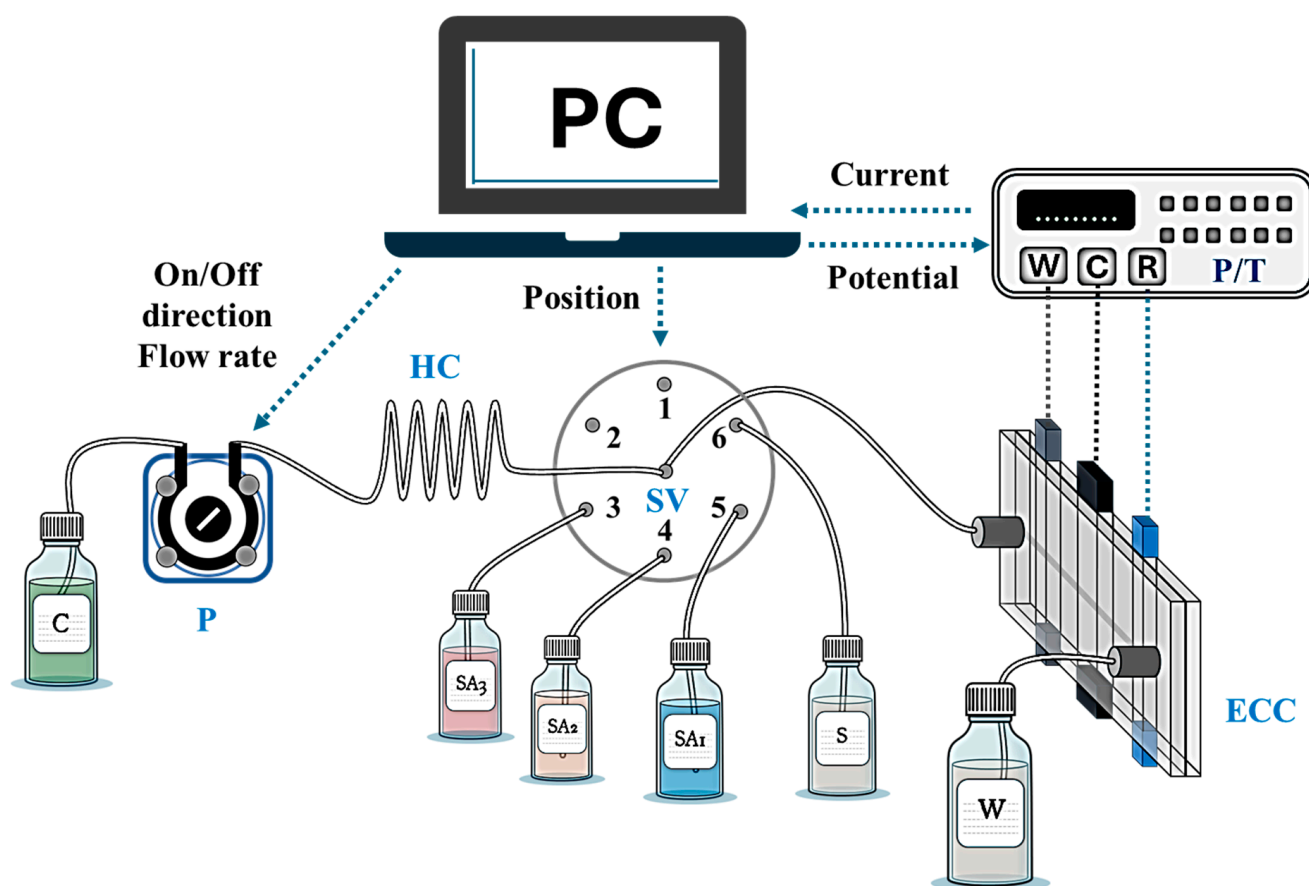


Figure 15. Schematic diagram of the SIA system used for Pb(II) analysis described by Kokkinos et al. (2016) [36]. The setup includes a selection valve (SV) connected to multiple sample inputs (S, SA₁, SA₂, SA₃), a carrier solution (C) containing HCl, and a peristaltic pump (P) for fluid movement. The system is controlled by a personal computer (PC), which regulates flow rate, direction, and valve position. Detection is performed via an electrochemical cell (ECC) connected to a potentiostat (P/T), with waste directed to W. Thick lines indicate flow lines, while thin lines represent control and data acquisition connections.

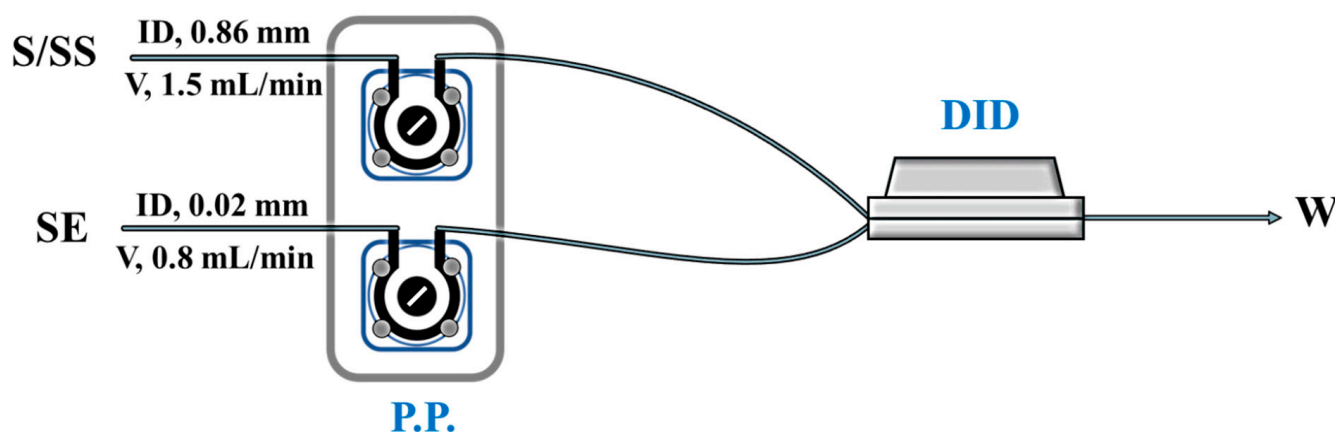


Figure 16. Schematic diagram of a flow system based on peristaltic pumps, as described by Knihnicki et al. (2023) [43]. The system includes two peristaltic pumps (P.P.) for delivering the sample or standard solution (S/SS) and supporting electrolyte (SE) to a Direct Injection Detector (DID). Waste is directed to the outlet (W). Flow rates are set at 1.5 mL/min for P1 and 0.08 mL/min for P2, with inner diameters (ID) of 0.86 mm and 0.02 mm, respectively.

These developments in electrochemical methods highlight the advantages of flow-based systems for trace metal determination, offering enhanced precision, sensitivity, and reproducibility across diverse environmental and food matrices.

2.4. Sample Introduction Methods

Flow Injection Analysis (FIA) has been easily coupled with various sample introduction techniques, including chemical vapor generation (CVG), an important method widely used in atomic spectrometry for its enhanced sensitivity and selectivity. A clear example of this is the previously cited work by Sánchez Trujillo et al. (2013) [29], where SPE is applied to improve efficiency in the determination. When performed efficiently, CVG can eliminate the need for solid-phase extraction (SPE). One common technique within CVG is hydride generation (HG), which allows the separation of lead in the form of PbH_4 from the sample matrix for subsequent determination. This is achieved using specific reagents and careful pH control, making HG the most widespread CVG technique for the determination of trace and ultratrace elements due to its high vapor generation efficiency and effective matrix separation. However, plumbane generation is not straightforward, and HG methods for lead are often insufficiently robust for routine analysis. The optimal pH range for Pb HG is very narrow, requiring strict acidity control for reliable results. In some cases, even the acid concentrations used for sample preservation can interfere with the process [49].

Schlotthauer et al. (2024) developed a Flow Injection hydride generation atomic absorption spectrometry (FI-HGAAS) method to address some of these challenges (Figure 17). The use of borate as a buffer significantly improved the method's robustness toward acidity compared to conventional non-buffered HG. Additionally, thiocyanate was employed as a masking agent to overcome the interference from Cu, Sb, and Sn in the HG reaction. The detection limit achieved was $0.3 \mu\text{g L}^{-1}$, while the quantification limit was $0.9 \mu\text{g L}^{-1}$. The method's linearity was validated between the LOQ and $15 \mu\text{g L}^{-1}$, with R^2 values consistently greater than 0.997 during sample analysis. Precision was evaluated using RSD ($n = 6$), with values of 0.78% for repeatability and 3.8% for intermediate precision, using samples with a lead concentration of $13 \mu\text{g L}^{-1}$. An analytical throughput of 25 samples per hour, with three replicates per measurement, was achieved. Trueness was confirmed through recovery assays, interlaboratory comparisons, and a reference method (two water samples), yielding satisfactory results. Percentage recoveries ranged from 94% to 106%, with an average of 98.2% and a standard deviation of 4.9% [46].

Another technique employed within CVG is metal ion-assisted photochemical vapor generation (PVG). Unlike HG, PVG does not require unstable reagents, allowing the direct determination of trace lead in complex environmental matrices such as soils, sediments, and seawater. This is achieved using free radicals generated by photoredox reactions in the presence of low-molecular-weight organic compounds [50].

An example of this is the FIA system developed by Gao et al. (2015) [3], which employed metal ion-assisted PVG coupled with multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) detection (Figure 18). The PVG efficiency for lead was significantly improved by using transition metal ions (Co^{2+} and Ni^{2+}) in 5% (v/v) formic acid solutions. This allowed for the determination of Pb in digests of sediment and soil samples, facilitated by the presence of coexisting transition metal ions, which enhanced the PVG reaction. A 22-fold increase in sensitivity was achieved with PVG compared to direct solution nebulization. The method detection limit for Pb was 0.005 ng g^{-1} , based on three times the standard deviation of the Pb concentration from the method blank containing 5% formic acid and $3.0 \mu\text{g g}^{-1} \text{ Ni}^{2+}$, using external calibration. The linear range of the method extended from 0.005 to 100 ng g^{-1} Pb, with a sample throughput of 10 samples per

hour. Precision was good, with an RSD of 3.0% obtained from replicate measurements of a $0.030 \mu\text{g g}^{-1}$ Pb standard solution in 5% formic acid under optimized conditions.

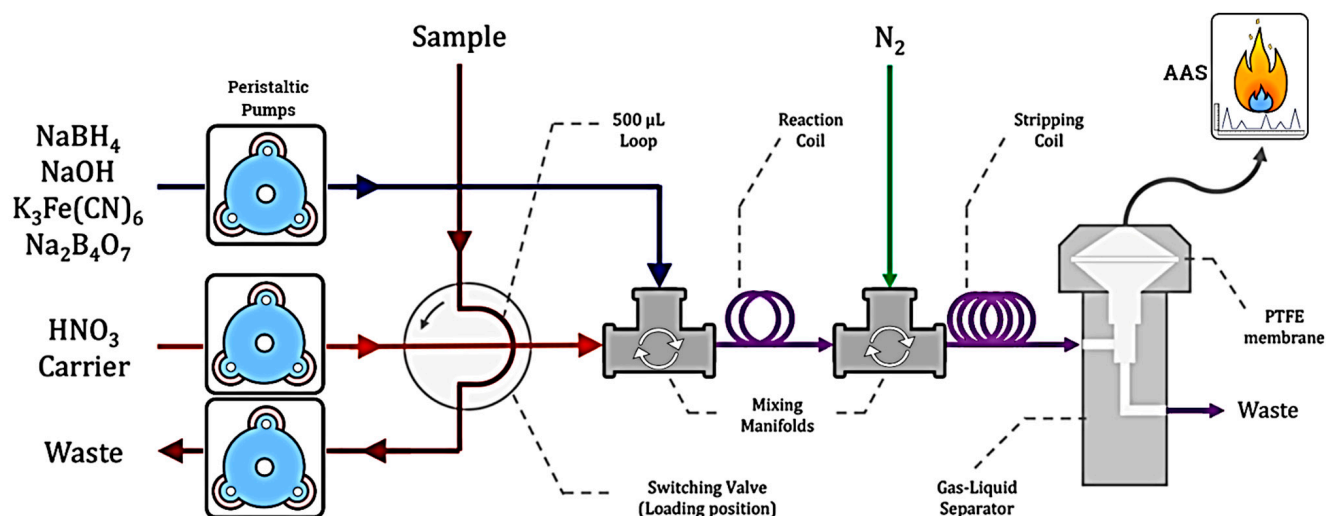


Figure 17. Diagram of FI-HGAAS system described by Schlotthauer et al. (2024) [46]. The system includes a peristaltic pump to deliver the sample and reagents along with the carrier. Samples pass through a loop and are mixed in the reaction coil before nitrogen gas (N_2) drives the mixture through a gas–liquid separator with a PTFE membrane. The resulting gas is directed to the AAS detector, while waste is managed through the outlet.

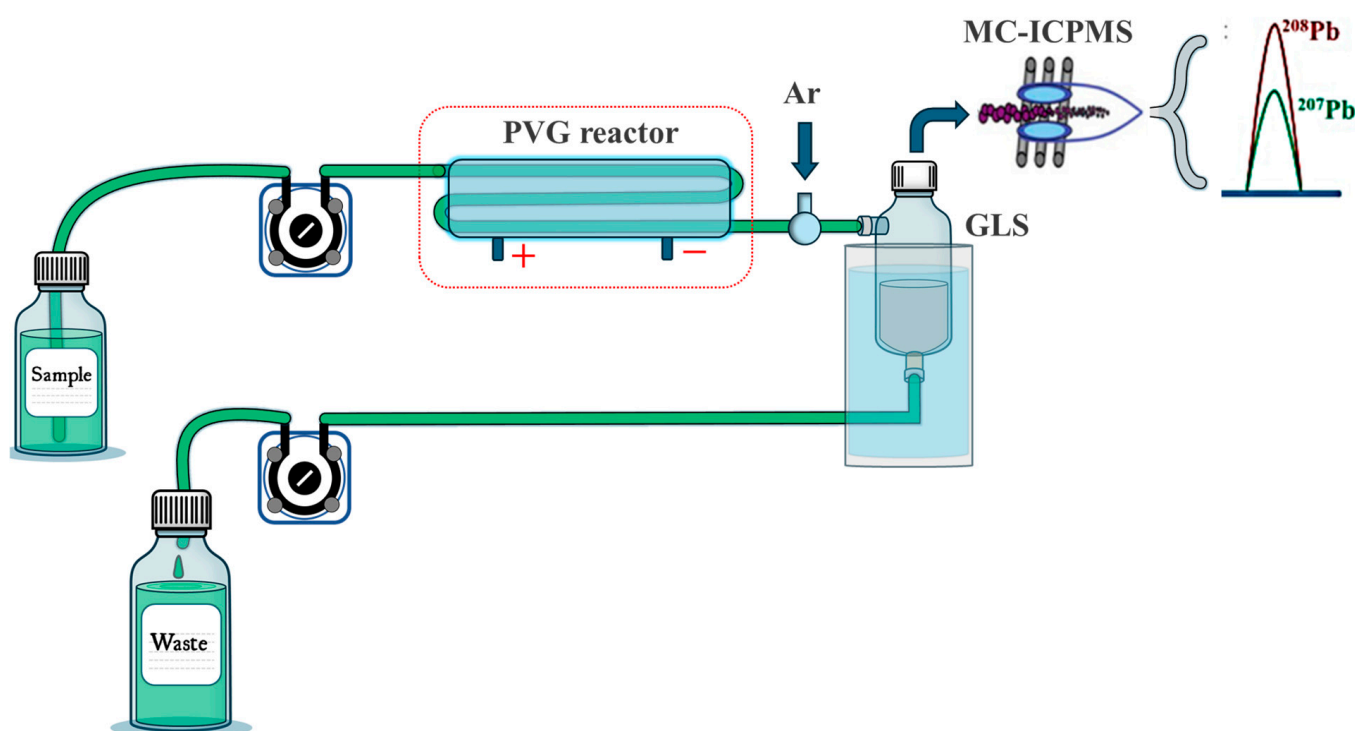


Figure 18. Schematic of the UV-Photochemical Vapor Generation (UV-PVG) system interfaced with MC-ICPMS for lead isotope analysis, as described by Gao et al. (2015) [3]. The system directs the sample solution into the PVG reactor, where vapor generation is enhanced under UV light. Argon gas (Ar) carries the vapor through a gas–liquid separator (GLS) and into the MC-ICPMS for the detection of lead isotopes, such as ^{207}Pb and ^{208}Pb . Waste is collected separately, ensuring a clean detection process.

The method's accuracy was demonstrated through the analysis of several environmentally certified reference materials (river water and sediments), yielding satisfactory results. High precision ($<0.4\%$ RSD) was achieved for Pb determinations in river water and sediments using isotope dilution calibration (Figure 18).

In 2017, Li et al. developed a sensitive, simple, and direct method for the accurate determination of trace lead in seawater samples using nickel ion-assisted PVG coupled with ICP-MS detection. The severe matrix effects of seawater, which often suppress lead signals, were effectively eliminated by using a mixture of $15 \mu\text{g g}^{-1} \text{Ni}^{2+}$ and 10% (v/v) formic acid as the photochemical reduction medium, making direct determination of lead in seawater samples feasible. The method detection limit was 0.003 ng g^{-1} , based on external calibration using solutions of 1.75% NaCl, 10% formic acid, and $15 \mu\text{g g}^{-1} \text{Ni}^{2+}$ in deionized water. The RSD of the measurement results was 3.7% ($n = 7$) in seawater spiked with $1 \text{ ng g}^{-1} \text{Pb}^{2+}$ solution. A good linear response was observed for Pb standard solutions prepared in the range of 0.02 to 200 ng g^{-1} in 1.75% NaCl [37].

The proposed method was successfully applied to the analysis of a seawater CRM, yielding results that were in agreement with certified values and confirming the method's accuracy. The method was also applied to three seawater samples (collected from Shanghai, Haikou, and Sanya, China), where spike recovery tests yielded recoveries ranging from 95.2% to 108.9% .

Table 2. Summary of Environmental Sustainability Evaluations for Automated Analytical Methods Using GAPI and AGREE Metrics in Chronological Order.

Method	GAPI Score	AGREE Score	Remarks	Reference
RFIA-FAAS con Zeolitas LTA/FAU	Moderate (Yellow grid)	0.79	Sustainable approach with reusable zeolites and minimized solvent use.	Yaneira Petit et al., 2013 [30]
SI-LAV-D/PME with CHCl_3	Moderate (Yellow grid)	0.77	Sustainable approach with minimal solvent use, reusable extraction chamber.	Mitani et al., 2013 [31]
FI-HG-ETAAS with PSTH-cpg	Moderate (Yellow grid)	0.81	Sustainable approach with reusable resins, low sample volume, and high accuracy.	Sánchez Trujillo et al., 2013 [29]
FI-HG-ETAAS with TS-gel	Moderate (Yellow grid)	0.75	Lower sensitivity and efficiency compared to PSTH-cpg; similar environmental impact.	
LOV-MSFIA-ICP-MS with Sr-Resin	Good (Green grid)	0.85	Automated, low sample and reagent usage, reusable sorbent; energy use could be optimized.	Beltrán et al., 2013 [4]
FI-FAAS with Amberlite XAD-16 resin	Moderate (Yellow grid)	0.84	Sustainable with reusable sorbent, low reagent volumes, and high efficiency.	Singh et al., 2014 [32]
Metal Ion-Assisted PVG with MC-ICPMS	Moderate (Yellow grid)	0.55	Simplified sample introduction, reduced reagent consumption, and energy-intensive instrumentation.	Gao et al., 2015 [3]
FI-AAS with Thiol-functionalized SBA-15	Moderate (Yellow grid)	0.64	Automated, reusable sorbent, minimal reagent volumes, moderately energy-intensive FAAS.	Zhao et al., 2015 [33]
SI-CC-LLME with FAAS	Moderate (Yellow grid)	0.60	Automated, low reagent consumption, reuse of components, limited by chloroform toxicity.	Mitani et al., 2015 [17]
LOV-HG-AFS with Pb-Resin	Moderate (Yellow grid)	0.64	Automated, low reagent consumption, reusable sorbent, limited by hazardous hydride reagents.	Beltrán et al., 2015 [5]
mSI-LOV Spectrophotometry	High (Green grid)	0.72	Automated, minimal waste, water-based reagents, limited by the use of Triton X-100.	Santos et al., 2015 [2]
FI-SPE-FAAS with Nobias Resin	Moderate (Yellow grid)	0.69	Automated, efficient reagent use, limited by the reliance on nitric acid as eluent.	Giakisikli et al., 2016 [34]

Table 2. Cont.

Method	GAPI Score	AGREE Score	Remarks	Reference
SISA with Plastic Fluidic Cells	Moderate (Yellow grid)	0.71	Automated, low waste generation, limited by plastic disposables and hazardous reagents.	Kokkinos et al., 2016 [36]
PVG-ICP-MS for Pb(II)	High (Green grid)	0.70	Automated, low reagent volumes, ultra-low detection limits, limited by ICP-MS energy use.	Li et al., 2017 [37]
FI-SCGD-AES with GO-SBA-15	Moderate (Yellow grid)	0.71	Automated, efficient reagent use, low sample volume, limited by nitric acid hazards.	Mo et al., 2017 [38]
3D-Printed MPFS for Pb(II)	High (Green grid)	0.71	Automated, low reagent volumes, reusable components, limited by nitric acid hazards.	Mattio et al., 2017 [20]
LLE: single-drop microextraction, colorimetric reaction with dithizone coupled to UV-VIS	Moderate (yellow)	0.74	Low volume of reagents and samples, but non-biobased reagents	Šrámková et al., 2018 [25]
CSDf-ME coupled to GF-AAS	Moderate (yellow)	0.64	Low extraction time but toxic reagents involved	Moinfar et al., 2018 [39]
MSFIA-LOV coupled to AAS	Moderate (yellow)	0.73	3D-printed application and two elements analyzed, but toxic reagents involved and low sample throughput	Mattio et al., 2018 [24]
SPE: with PP as sorbent material and DDTC as chelating reagent coupled to F-AAS	Moderate (yellow)	0.73	A few steps involved in the extraction process, but non-biobased reagents	Kazantzi et al., 2019 [40]
SPE: D μ SPE Extraction with benzophenone coupled to AAS		0.59	Several steps involved in the sample preconcentration process (12), and non-biobased reagents	Stamna et al., 2020 [18]
SPE: Pb-Resin, colorimetric reaction with PAR coupled to UV-VIS	Moderate (yellow)	0.70	Variable sample volume used, but non-biobased reagents	Rodríguez-Maese et al., 2020 [9]
SPE with PDPS coupled to FAAS	Moderate (yellow)	0.79	Fast analysis time and few steps involved in the analysis	Lazaridou et al., 2020 [41]
SPE: O-CNTs and F-CNTs coupled to FAAS	Moderate (yellow)	0.69	High sample throughput, but a large volume of sample required	Bajaj et al., 2021 [42]
Colorimetric reaction with DBHQ coupled to UV-VIS	Moderate (yellow)	0.76	High sample throughput, but sample preparation involved toxic reagents	Muklive et al., 2022 [13]
LLE: DLLME, colorimetric reaction with dithizone coupled to UV-VIS	Moderate Green	0.81	Greener alternatives used for extraction	Gonçalves Santos et al., 2022 [26]
Colorimetric reaction with 4-MDD coupled to UV-VIS	Moderate (yellow)	0.75	High sample throughput and low reagent volume	Jassim et al., 2023 [14]
Electrochemical reaction and voltammetry	Green	0.97	Environmentally friendly, portable, and highly efficient analytical method	Knihnicki et al., 2023 [43]
SPE: MSPE with M@GO-TS coupled to HPLC-ICP-MS	Moderate (yellow)	0.83	Reusable sorbent material, small waste volumes, and automation enhance greenness.	Montoro-Leal et al., 2023 [44]
LLE: LPME using NADES coupled to FAAS	Green	0.94	Environmentally friendly, automated system with high precision and minimal waste.	Christoforou et al., 2024 [45]
HG coupled with AAS	Moderate (yellow)	0.72	Robust method but longer analysis time	Schlotthauer et al., 2024 [46]

3. Environmental Sustainability of Automated Analytical Methods

The assessment of the environmental sustainability or “greenness” of automated analytical methods has been included to offer a broad exploration of their eco-friendliness.

This evaluation utilizes two widely accepted tools: the Green Analytical Procedure Index (GAPI) and the Analytical Greenness Calculator (AGREE). These instruments enable a thorough examination of different techniques by considering aspects such as reagent consumption, energy use, waste generation, and sample handling.

The GAPI tool offers a visual, semi-quantitative evaluation of the ecological impact at each stage of an analytical process. Its traffic light-style diagram identifies areas requiring improvement, focusing on factors such as sample preparation, reagent toxicity, waste disposal, and instrumentation. The color-coded grid illustrates the environmental sustainability of each technique, with green signifying eco-friendly practices and red highlighting areas that need attention [51].

In contrast, the AGREE metric provides a numerical evaluation of a method's environmental performance based on the 12 principles of green analytical chemistry. It consolidates these principles into a single score between 0 (least sustainable) and 1 (most sustainable), enabling straightforward comparisons across methods and offering an overall measure of ecological compatibility [51].

This analysis provides a general overview of the environmental sustainability of the reviewed methods. As summarized in Table 2, it highlights several key findings:

1. **Automation and Miniaturization:** Automated systems, such as Multisyringe Flow Injection Analysis (MSFIA) and Lab-On-Valve (LOV), present notable benefits in reducing the use of reagents and minimizing waste. These setups often incorporate reusable components, such as sorbent resins, which enhance their GAPI and AGREE scores. For instance, the LOV-MSFIA method analyzed by Beltrán et al. (2013) achieves outstanding environmental performance, with an AGREE score of 0.85, owing to low sample and reagent volumes coupled with automation efficiencies [4].
2. **Green Solvents and Solvent-Free Approaches:** Techniques utilizing greener alternatives, such as natural deep eutectic solvents (NADES), are distinguished by their minimal environmental impact. These strategies reduce dependence on toxic chemicals while ensuring high analytical accuracy. For example, the NADES-based microextraction paired with FAAS, as demonstrated by Christoforou et al. (2024), attained an AGREE score of 0.94, reflecting its excellent ecological profile [45].
3. **Reusable Components:** Methods that incorporate renewable materials, such as zeolites or ion-exchange resins, also show strong environmental performance. These recyclable sorbents not only lower waste production but also improve overall method efficiency. For instance, the FI-HG-ETAAS technique employing PSTH-cpg achieved an impressive AGREE score of 0.81, attributed to the use of reusable resins and reduced sample quantities [29].
4. **Energy Usage:** While automation and advanced technologies enhance analytical accuracy, they can occasionally lead to higher energy consumption. Methods like PVG-ICP-MS, despite their remarkable sensitivity and low reagent usage, require energy optimization to further enhance their sustainability [37].

4. Trends and Future Perspectives

The development and implementation of flow-based analytical systems for the detection of trace metals, particularly lead, have seen significant advancements in recent years. These methods, which often combine preconcentration techniques like SPE with highly sensitive detection technologies such as flame atomic absorption spectrometry (FAAS) and inductively coupled plasma mass spectrometry (ICP-MS), continue to evolve toward greater automation, sensitivity, and environmental sustainability. A notable trend is the increasing integration of miniaturized and 3D-printed components, as demonstrated by Mattio et al. (2017 and 2018) [20,24], where 3D-printed multipumping flow systems enhanced preci-

sion and reduced reagent consumption. This approach improves system efficiency while lowering operational costs, making it feasible for large-scale environmental monitoring.

Automation and multi-sample analysis have become focal points for improving throughput without compromising accuracy. For example, the fully automated FIA-FAAS systems developed by Singh et al. (2014) [32] and Zhao et al. (2015) [33] have demonstrated that high sensitivity and fast sample processing can be achieved, even for trace-level detection of Pb(II) in complex matrices. These systems are particularly beneficial in routine monitoring applications, where speed and reliability are critical.

Another emerging trend is the use of novel sorbent materials, such as functionalized mesoporous materials (Zhao et al., 2015) [33] and specialized resins like Nobias chelate PA-1 (Giakisikli et al., 2016) [34]. These materials exhibit enhanced selectivity and adsorption capacity for metal ions, leading to improved detection limits and broader application scopes in environmental and biological samples. The ability of these materials to retain efficiency over numerous analytical cycles further underscores their potential for sustainable and cost-effective usage in flow-based systems.

Looking forward, integrating green chemistry principles into analytical methodologies is expected to drive the next wave of innovations. The replacement of toxic reagents and solvents with environmentally benign alternatives is already being explored, with promising results. For instance, systems utilizing natural deep eutectic solvents (NADES) as extraction media offer an eco-friendly alternative without sacrificing analytical performance (Christoforou et al., 2024) [45]. Additionally, the miniaturization of systems and the reduction in sample and reagent volumes are in line with the trend toward more sustainable practices in analytical chemistry.

Moreover, the Internet of Things (IoT) and advancements in smart analytical devices offer new opportunities for remote, real-time monitoring of contaminants. The development of portable flow-based systems equipped with wireless communication technologies could allow for continuous environmental surveillance, transmitting real-time data to centralized monitoring systems. This trend aligns with the global shift towards more dynamic and responsive environmental management strategies, particularly in the face of increasing pollution and regulatory pressures.

The future of flow-based analytical systems will likely see further convergence with these technological innovations, leading to systems that are faster, more efficient, and capable of operating autonomously in the field. With continued advancements in materials science, automation, and digital integration, it is foreseeable that these systems will play a pivotal role in addressing the growing demand for reliable, high-throughput monitoring of trace metals in diverse environmental and biological matrices.

5. Conclusions

Flow-based analytical systems have demonstrated remarkable effectiveness in detecting and quantifying trace levels of lead (Pb), a toxic contaminant with serious health and environmental implications. These systems have achieved exceptional sensitivity, with the best detection limit reported at $0.003 \mu\text{g L}^{-1}$ by Sánchez Trujillo et al. (2013) [29], making them highly reliable for monitoring Pb in water, soil, and biological samples. Additionally, the sample throughput of these methods can be as high as 55 samples per hour, as demonstrated by Santos et al. (2015) [2], reinforcing their suitability for routine analyses.

Colorimetric techniques employing UV-VIS detectors hold significant potential for in-situ applications, enabling real-time field monitoring and immediate data acquisition. Notable examples include the system developed by Mattio et al. (2017) [20], which integrated 3D-printed components to enhance precision and portability, making it particularly suitable for on-site lead detection in natural waters. Similarly, Rodríguez-Maese et al. (2020) devel-

oped an MSFIA-LOV system that utilized UV-VIS detection in a liquid waveguide capillary cell, achieving successful automated and portable Pb analysis in environmental samples. These advancements highlight the growing feasibility of compact, field-deployable systems that provide rapid responses to contamination [9].

Recent innovations have led to the miniaturization and portability of these systems, aligning with green chemistry principles by reducing reagent consumption and analysis time. The development of compact, field-deployable systems significantly enhances their efficiency and effectiveness in environmental monitoring.

In summary, flow-based analytical systems are advancing towards increased automation, sensitivity, and portability, making them essential tools for proactive contaminant management and real-time environmental assessment. These developments highlight the potential for widespread application in remote monitoring, supporting dynamic strategies for contaminant control.

Real-time monitoring of Pb is becoming increasingly important to rapidly detect contamination events and respond to environmental hazards. Advances in automation and the integration of digital technologies facilitate continuous, remote monitoring, which is key to managing pollution and protecting public health.

Furthermore, the trend towards miniaturization in flow-based systems is driving the development of portable and cost-effective devices, enabling on-site analyses with reduced reagent and sample volumes. These innovations enhance the practicality and efficiency of these systems while aligning with the growing demand for more sustainable and accessible analytical methods.

In conclusion, flow-based systems are highly effective for Pb detection and other trace metals, achieving remarkable detection limits and sample throughput rates. The continuous evolution toward real-time monitoring and miniaturization will be essential for addressing future environmental and health challenges.

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Abbreviations

AFS	Atomic Fluorescence Spectrometry
APDC	Ammonium Pyrrolidine Dithiocarbamate
CVG	Chemical Vapor Generation
CSDF-ME	Continuous Sample Drop Flow Microextraction
DBHQ	5,7-Dibromo-8-Hydroxyquinoline
DDTC	Dithiocarbamate
DLLME	Dispersive Liquid–Liquid Microextraction
Et-AAS	Electrothermal Atomic Absorption Spectrometry

FAAS	Flame Atomic Absorption Spectrometry
FDSE	Fabric Disk Sorptive Extraction
FIA	Flow Injection Analysis
GF-AAS	Graphite Furnace Atomic Absorption Spectrometry
GO-SBA-15	Graphene Oxide Functionalized SBA-15
HG	Hydride Generation
HG-ETAAS	Hydride Generation-Electrothermal Atomic Absorption Spectrometry
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
LOD	Limit of Detection
LOQ	Limit of Quantification
LOV	Lab-On-Valve
LIS	Lab-In-Syringe
LLE	Liquid–Liquid Extraction
LPME	Liquid-Phase Microextraction
LWCC	Liquid Waveguide Capillary Cell
MC-ICPMS	Multi-Collector Inductively Coupled Plasma Mass Spectrometry
MIBK	Methyl Isobutyl Ketone
MSFIA	Multisyringe Flow Injection Analysis
MSPE	Magnetic Solid-Phase Extraction
MWCNTs	Multi-Walled Carbon Nanotubes
NADES	Natural Deep Eutectic Solvents
Pb	Lead
PVG	Photochemical Vapor Generation
RSD	Relative Standard Deviation
SDME	Single-Drop Microextraction
SI-LAV	Sequential Injection Lab-At-Valve
SIA	Sequential Injection Analysis
SPCEs	Screen-Printed Carbon Electrodes
SPE	Solid-Phase Extraction

References

1. Abadin, H.; Taylor, J.; Buser, M.; Scinicariello, F.; Przybyla, J.; Klotzbach, J.M.; Diamond, G.L.; Citra, M.; Chappell, L.L.; McIlroy, L.A. Chapter 1: Relevance to Public Health. In *Toxicological Profile for Lead*; Division of Toxicology and Human Health Sciences, ATSDR: Atlanta, GA, USA, 2020; pp. 1–9. Available online: <https://www.atsdr.cdc.gov/toxprofiles/tp13.pdf> (accessed on 21 February 2024).
2. Santos, I.C.; Mesquita, R.B.; Rangel, A.O. Screening of Cadmium and Lead in Potentially Contaminated Waters Using a Spectrophotometric Sequential Injection Lab-on-Valve Methodology. *Talanta* **2015**, *143*, 359–365. [CrossRef] [PubMed]
3. Gao, Y.; Xu, M.; Sturgeon, R.E.; Mester, Z.; Shi, Z.; Galea, R.; Yang, L. Metal Ion-Assisted Photochemical Vapor Generation for the Determination of Lead in Environmental Samples by Multicollector-ICPMS. *Anal. Chem.* **2015**, *87*, 4495–4502. [CrossRef] [PubMed]
4. Beltrán, B.; Avivar, J.; Mola, M.; Ferrer, L.; Cerdà, V.; Leal, L.O. Automated Method for Simultaneous Lead and Strontium Isotopic Analysis Applied to Rainwater Samples and Airborne Particulate Filters (PM10). *Environ. Sci. Technol.* **2013**, *47*, 9850–9857. [CrossRef] [PubMed]
5. Beltrán, B.; Leal, L.O.; Ferrer, L.; Cerdà, V. Determination of Lead by Atomic Fluorescence Spectrometry Using an Automated Extraction/Pre-Concentration Flow System. *J. Anal. At. Spectrom.* **2015**, *30*, 1072–1079. [CrossRef]
6. World Health Organization (WHO). *WHO Guidelines for Drinking-Water Quality*, 3rd ed.; WHO: Geneva, Switzerland, 2004.
7. Environmental Protection Agency (EPA). *Contaminantes en Agua Potable*; Office of Water (4100T): Washington, DC, USA, 2009. Available online: <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockkey=60001N8P.txt> (accessed on 3 February 2023).
8. U.S. Environmental Protection Agency (EPA). Basic Information About Lead in Drinking Water. EPA. Available online: <https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water#:~:text=EPA%20has%20set%20the%20maximum,even%20at%20low%20exposure%20levels> (accessed on 22 October 2024).
9. Rodríguez-Maese, R.; Ferrer, L.; Cerdà, V.; Leal, L.O. Fully Automatic System for Lead Monitoring in Water. *Microchem. J.* **2020**, *154*, 104550. [CrossRef]

10. Cerdá, V.; Ferrer, L.; Avivar, J.; Cerda, A. The Need for Analysis Automation. In *Flow Analysis: A Practical Guide*; Newnes: Oxford, UK, 2014; Chapter 1.1, pp. 2–3.
11. Cerdá, V.; Ferrer, L.; Avivar, J.; Cerda, A. Flow Injection Analysis. In *Flow Analysis: A Practical Guide*; Newnes: Oxford, UK, 2014; Chapter 1.3, pp. 7–9.
12. Trojanowicz, M.; Kołacińska, K. Recent Advances in Flow Injection Analysis. *Analyst* **2016**, *141*, 2085–2139. [[CrossRef](#)]
13. Muklive, K.S.K.A.J.; Shami, D.Z. Simple Method for the Determination of Lead (II) Content by Normal Flow Injection Spectrophotometric Using 5,7-Dibromo-8-Hydroxyquinoline Reagent. *NeuroQuantology* **2022**, *20*, 155. [[CrossRef](#)]
14. Jassim, T.J.; Tareh, R.K. New Design Valve in Flow Injection System for the Determination of Pb(II) in Biological and Environmental Samples. *Indones. J. Chem.* **2023**, *23*, 1129–1137. [[CrossRef](#)]
15. Cerdá, V.; Ferrer, L.; Avivar, J.; Cerda, A. Sequential Injection Analysis. In *Flow Analysis: A Practical Guide*; Newnes: Oxford, UK, 2014; Chapter 1.4, p. 9.
16. Mesquita, R.B.; Rangel, A.O. A Review on Sequential Injection Methods for Water Analysis. *Anal. Chim. Acta* **2009**, *648*, 7–22. [[CrossRef](#)] [[PubMed](#)]
17. Mitani, C.; Anthemidis, A.N. An Automatic Countercurrent Liquid–Liquid Micro-Extraction System Coupled with Atomic Absorption Spectrometry for Metal Determination. *Talanta* **2015**, *133*, 77–81. [[CrossRef](#)] [[PubMed](#)]
18. Stamna, A.; Anthemidis, A.N. Sequential Injection Solvent Dispersive Micro Solid Phase Extraction (SI-SD- μ SPE) Platform Coupled with Atomic Absorption Spectrometry for Lead Determination in Water Samples. *Microchem. J.* **2020**, *156*, 104820. [[CrossRef](#)]
19. Cerdá, V.; Ferrer, L.; Avivar, J.; Cerda, A. Multipumping flow systems. In *Flow Analysis: A Practical Guide*; Newnes: Oxford, UK, 2014; Chapter 1.7, p. 19.
20. Mattio, E.; Robert-Peillard, F.; Branger, C.; Puzio, K.; Margailan, A.; Brach-Papa, C.; Coulomb, B. 3D-Printed Flow System for Determination of Lead in Natural Waters. *Talanta* **2017**, *168*, 298–302. [[CrossRef](#)] [[PubMed](#)]
21. Cerdá, V.; Ferrer, L.; Avivar, J.; Cerda, A. Multisyringe flow injection analysis. In *Flow Analysis: A Practical Guide*; Newnes: Oxford, UK, 2014; Chapter 1.6, p. 16.
22. Cerdá, V.; Ferrer, L.; Avivar, J.; Cerda, A. Lab on valve. In *Flow Analysis: A Practical Guide*; Newnes: Oxford, UK, 2014; Chapter 1.8, p. 21.
23. Cocovi-Solberg, D.J.; Rosende, M.; Michalec, M.; Miró, M. 3D Printing: The Second Dawn of Lab-on-Valve Fluidic Platforms for Automatic (Bio)Chemical Assays. *Anal. Chem.* **2018**, *91*, 1140–1149. [[CrossRef](#)] [[PubMed](#)]
24. Mattio, E.; Robert-Peillard, F.; Vassalo, L.; Branger, C.; Margailan, A.; Brach-Papa, C.; Coulomb, B. 3D-Printed Lab-on-Valve for Fluorescent Determination of Cadmium and Lead in Water. *Talanta* **2018**, *183*, 201–208. [[CrossRef](#)]
25. Šrámková, I.H.; Horstkotte, B.; Fikarová, K.; Sklenářová, H.; Solich, P. Direct-Immersion Single-Drop Microextraction and In-Drop Stirring Microextraction for the Determination of Nanomolar Concentrations of Lead Using Automated Lab-In-Syringe Technique. *Talanta* **2018**, *184*, 162–172. [[CrossRef](#)]
26. Santos, F.G.; Maya, F.; Dos Reis, B.F.; Zagatto, E.A.G.; Cerdà, V. Flow-Based Determination of Lead Exploiting In-Syringe Dispersive Liquid-Liquid Micro-Extraction in Xylene and Integrated Spectrophotometric Detection. *Talanta* **2022**, *247*, 123528. [[CrossRef](#)] [[PubMed](#)]
27. Rodríguez, R.; Avivar, J.; Leal, L.O.; Cerdà, V.; Ferrer, L. Strategies for Automating Solid-Phase Extraction and Liquid-Liquid Extraction in Radiochemical Analysis. *TrAC Trends Anal. Chem.* **2016**, *76*, 145–152. [[CrossRef](#)]
28. Ozbek, N.; Baysal, A.; Akman, S.; Dogan, M. Solid-Phase Extraction. In *Analytical Separation Science*; Wiley: Hoboken, NJ, USA, 2015; pp. 1571–1594. [[CrossRef](#)]
29. Trujillo, I.S.; Castillo, M.L.A.; Pavón, J.M.C.; Alonso, E.I.V.; de Torres, A.G. Flow Injection On-Line Solid Phase Extraction for Ultra-Trace Lead Determination with Hydride Generation Electrothermal Atomic Absorption Spectrometry. *Anal. Methods* **2013**, *5*, 2551–2557. [[CrossRef](#)]
30. de Pe, Y.P.; Rondón, W. Linde Type A Zeolite and Type Y Faujasite as a Solid-Phase for Lead, Cadmium, Nickel and Cobalt Preconcentration and Determination Using a Flow Injection System Coupled to Flame Atomic Absorption Spectrometry. *Am. J. Anal. Chem.* **2013**, *4*, 387–397. [[CrossRef](#)]
31. Mitani, C.; Anthemidis, A.N. On-Line Liquid Phase Micro-Extraction Based on Drop-in-Plug Sequential Injection Lab-at-Valve Platform for Metal Determination. *Anal. Chim. Acta* **2013**, *771*, 50–55. [[CrossRef](#)] [[PubMed](#)]
32. Singh, S.; Saxena, R. On-Line Preconcentration and Determination of Lead in Water by Flow Injection-Flame Atomic Absorption Spectroscopy Using Amberlite XAD-16 Functionalized with Xylenol Orange. *Int. J. Adv. Res. Sci. Eng.* **2014**, *3*, 172–184.
33. Zhao, S.L.; Chen, F.S.; Zhang, J.; Ren, S.B.; Liang, H.D.; Li, S.S. On-Line Flame AAS Determination of Traces Cd(II) and Pb(II) in Water Samples Using Thiol-Functionalized SBA-15 as Solid Phase Extractant. *J. Ind. Eng. Chem.* **2015**, *27*, 362–367. [[CrossRef](#)]
34. Giakisiikli, G.; Zachariadis, P.; Kila, I.; Teshima, N.; Anthemidis, A. Flow Injection Solid Phase Extraction for Trace Metal Determination Using a Chelating Resin and Flame Atomic Absorption Spectrometry Detection. *Anal. Lett.* **2016**, *49*, 929–942. [[CrossRef](#)]

35. Anthemidis, A.; Kazantzi, V.; Samanidou, V.; Kabir, A.; Furton, K.G. An Automated Flow Injection System for Metal Determination by Flame Atomic Absorption Spectrometry Involving On-Line Fabric Disk Sorptive Extraction Technique. *Talanta* **2016**, *156*, 64–70. [\[CrossRef\]](#)
36. Kokkinos, C.; Economou, A.; Goddard, N.G.; Fielden, P.R.; Baldock, S.J. Determination of Pb(II) by Sequential Injection/Stripping Analysis at All-Plastic Electrochemical Fluidic Cells with Integrated Composite Electrodes. *Talanta* **2016**, *153*, 170–176. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Li, S.; Gao, Y.; Yu, Y.; He, H.; Hu, X.; Ni, S.; Liu, R. Direct Determination of Trace Lead in Seawater by Inductively Coupled Plasma Mass Spectrometry After Photochemical Vapor Generation. *At. Spectrosc.* **2017**, *38*, 37–43. [\[CrossRef\]](#)
38. Mo, J.; Zhou, L.; Li, X.; Li, Q.; Wang, L.; Wang, Z. On-Line Separation and Pre-Concentration on a Mesoporous Silica-Grafted Graphene Oxide Adsorbent Coupled with Solution Cathode Glow Discharge-Atomic Emission Spectrometry for the Determination of Lead. *Microchem. J.* **2017**, *130*, 353–359. [\[CrossRef\]](#)
39. Moinfar, S.; Khayatian, G.; Jamil, L.A. Semi-Automated Continuous Sample Drop Flow Microextraction with Swift Preconcentration and Atomic Absorption Spectrometry Determination of Lead in Water and Apple Leaves. *J. Iran. Chem. Soc.* **2018**, *15*, 2511–2518. [\[CrossRef\]](#)
40. Kazantzi, V.; Drosaki, E.; Skok, A.; Vishnikin, A.B.; Anthemidis, A. Evaluation of Polypropylene and Polyethylene as Sorbent Packing Materials in On-Line Preconcentration Columns for Trace Pb(II) and Cd(II) Determination by FAAS. *Microchem. J.* **2019**, *148*, 514–520. [\[CrossRef\]](#)
41. Lazaridou, E.; Kabir, A.; Furton, K.G.; Anthemidis, A. A Novel Glass Fiber Coated with Sol–Gel Poly-Diphenylsiloxane Sorbent for the On-Line Determination of Toxic Metals Using Flow Injection Column Preconcentration Platform Coupled with Flame Atomic Absorption Spectrometry. *Molecules* **2020**, *26*, 9. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Bajaj, S.; Jain, V.; Sharma, N.; Tiwari, S.; Saxena, R. Efficient Lead Preconcentration Using Two Chemically Functionalized Carbon Nanotubes in Hyphenated Flow Injection-Flame Atomic Absorption Spectrometry System. *J. Chromatogr. A* **2021**, *1638*, 461888. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Knihnicki, P.; Kusior, B.; Paluch, J.; Kościelniak, P.; Kochana, J. A Novel Approach of Flow System with a 3D-Printed Direct Injector Detector for Electrochemical Determination of Cadmium and Lead. *Microchem. J.* **2023**, *195*, 109514. [\[CrossRef\]](#)
44. Montoro-Leal, P.; García-Mesa, J.C.; Morales-Benítez, I.; Vázquez-Palomo, L.; López Guerrero, M.D.M.; Vereda Alonso, E.I. Synthesis of a Novel Magnetic Nanomaterial for the Development of a Multielemental Speciation Method of Lead, Mercury, and Vanadium via HPLC-ICP MS. *Microchim. Acta* **2023**, *190*, 296. [\[CrossRef\]](#)
45. Christoforou, V.; Manousi, N.; Zacharis, C.K.; Anthemidis, A. A Green Flow-Batch Liquid Phase Microextraction Lab-in-Syringe Platform Based on Natural Deep Eutectic Solvents for Toxic Metal Determination. *Sustain. Chem. Pharm.* **2024**, *39*, 101567. [\[CrossRef\]](#)
46. Schlotthauer, J.; Mántaras, L.; Brusa, L.; Sigrist, M. A Robust Method for the Determination of Lead in Water Samples Using Flow Injection Hydride Generation Atomic Absorption Spectrometry. *Spectrochim. Acta Part B* **2024**, *212*, 106851. [\[CrossRef\]](#)
47. Fernandes, G.M.; Silva, W.R.; Barreto, D.N.; Lamarca, R.S.; Gomes, P.C.F.L.; da S Petrucci, J.F.; Batista, A.D. Novel Approaches for Colorimetric Measurements in Analytical Chemistry—A Review. *Anal. Chim. Acta* **2020**, *1135*, 187–203. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Kurbanoglu, S.; Unal, M.A.; Ozkan, S.A. Recent Developments on Electrochemical Flow Injection in Pharmaceuticals and Biologically Important Compounds. *Electrochim. Acta* **2018**, *287*, 135–148. [\[CrossRef\]](#)
49. Gil, R.A.; Pacheco, P.H.; Cerutti, S.; Martinez, L.D. Vapor Generation–Atomic Spectrometric Techniques. Expanding Frontiers Through Specific-Species Preconcentration. A Review. *Anal. Chim. Acta* **2015**, *875*, 7–21. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Sturgeon, R.E. Photochemical Vapor Generation: A Radical Approach to Analyte Introduction for Atomic Spectrometry. *J. Anal. At. Spectrom.* **2017**, *32*, 2319–2340. [\[CrossRef\]](#)
51. Yin, L.; Yu, L.; Guo, Y.; Wang, C.; Ge, Y.; Zheng, X.; Zhang, N.; You, J.; Zhang, Y.; Shi, M. Green Analytical Chemistry Metrics for Evaluating the Greenness of Analytical Procedures. *J. Pharm. Anal.* **2024**, *14*, 101013. [\[CrossRef\]](#)

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