

# Lead Detection in Drinking Water: A Comparative Evaluation of Modern Analytical and Sensor-Based Approaches

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**Abstract** - Lead (Pb<sup>2+</sup>) contamination in drinking water and the environment is a major cause of emerging public health threats worldwide due to its non-biodegradable nature and highly toxic effects, which include neurotoxicity, developmental delays, and renal dysfunction. The contamination is primarily caused by old lead-based plumbing systems, industrial effluents, pesticide leaching, and fertilizer runoff, especially in densely populated or heavily farmed areas. Given the health risks associated with even minimal exposure, there is an ongoing need to develop and improve sensitive, selective, and scalable detection methods. This review systematically outlines the progress of analytical techniques for lead detection in water from the early 20th century to the present. It begins with gravimetric and colorimetric tests and highlights key milestones such as Atomic Absorption Spectroscopy (AAS), Inductively Coupled Mass Spectrometry (ICP-MS), and various voltammetric methods. Recent advances, especially in electrochemical sensors, fluorescence-based probes, and nanomaterial-enhanced platforms, have significantly improved detection limits, portability, and real-time capabilities. By comparing these technologies based on factors like detection limit, specificity, cost, operational complexity, and field applicability, the review identifies trends and prospects for future intelligent water quality monitoring systems. Focus is given to emerging techniques that integrate nanotechnology, microfluidics, and AI, paving the way for next generation decentralized environmental diagnostics.

**Keywords** - Drinking water contamination, Electrochemical sensors, Nanomaterials, Environmental monitoring, Portable water testing, Heavy metals, Point-of-care diagnostics.

## I. INTRODUCTION

A safe and clean water supply is one of the basic human rights and a very important factor in public health. Unfortunately, for several decades, industrialization has increased. Mining has been carried out without control, lead plumbing has been used, and there has also been an unrestrained application of the agrochemical along with these. Water sources have been continuously polluted with poisonous heavy metals, chiefly lead (Pb<sup>2+</sup>), because of these facts. Lead is a non-biodegradable, toxic substance that accumulates in the body and is very dangerous even in small quantities, with the World Health Organization setting a limit of only 10 µg/L in drinking water. This is made worse by the fact that lead contamination is usually undetectable by taste, odor, or color; however, it will remain for a long time and have a significant impact on health.

The main sources of lead in water are corroded lead pipes, materials for plumbing, industrial waste, battery recycling plants, and, most importantly, through fertilizers and pesticides that are leached in agricultural runoff. In cities, the water system infrastructure has been there for a long time, and the water supply may deteriorate, or parts may become corroded over time, thus polluting the water with lead. As well as in rural and peri-urban areas, the excessive use of phosphate-based fertilizers and lead-containing compounds leads to leaching into groundwater and rivers. This matter is highly worsened by the lack of water purification installations and the weak execution of regulations in many developing countries. Polluted water not only affects those who drink it but also can be the source of contamination in the whole food chain if it is used for irrigation or for animals to drink. The biological impacts of lead intake are very damaging and have the most severe unintended effects on vulnerable populations like children, women who are pregnant women, and people who have health problems. If lead is found in water and a person is exposed to it for a long time, it can cause neurotoxicity, problems in cognitive development, kidney dysfunction, heart diseases, and reproductive toxicity. In children, even the smallest dose can affect their IQ, attention span, and school performance irreversibly. Taking into consideration these serious health implications, early recognition and constant supervision of lead pollution in water are the necessities of the hour.

An ideal solution to address this crisis must be multifaceted, combining early detection, scalability, affordability, and portability. Traditional centralized lab-based detection systems, though highly accurate, are often expensive, time-consuming, and require skilled personnel. Moreover, such methods are not always feasible in remote

or resource-constrained settings. Therefore, there is a pressing need for innovative sensor technologies that are affordable, sensitive, selective, and capable of providing near real-time results in the field or at the point of use. These sensors should ideally be user-friendly and adaptable to various water matrices, including tap water, groundwater, surface water, and industrial effluents. Integration with IoT or smartphone interfaces for data collection and cloud-based monitoring further enhances the utility of such systems in modern-day environmental surveillance.

Over the past century, the field of lead detection in aqueous environments has witnessed remarkable technological evolution from basic gravimetric analysis to modern nanomaterial-integrated smart sensors. The journey began in 1907 with gravimetric methods, where lead ions were precipitated and quantified by mass, a reliable but time-intensive process unsuitable for trace detection. The 1950s introduced colorimetric methods using chromogenic reagents like dithizone, which enabled semi-quantitative field testing but suffered from limited selectivity. The breakthrough came in the 1970s with Atomic Absorption Spectroscopy (AAS), which brought higher sensitivity and accuracy, solidifying its role in regulated testing. The 1980s saw the emergence of Inductively Coupled Plasma Mass Spectrometry (ICP-MS), capable of ultra-trace detection and multi-element analysis, albeit with high cost and operational complexity. By the 1990s, electrochemical voltammetry offered portable, field-deployable detection using redox principles. The early 2000s refined spectrophotometry using advanced ligands for better selectivity. Electrochemical sensors, introduced in 2008, enhanced real-time detection using nanomaterials. In the 2010s, DNAzymes and carbon dots were fluorometric biosensors that were based on fluorescence, pushing specificity and miniaturization. Nowadays, the aptamer-functionalized nanomaterial sensors that are combined with microfluidics and the smartphone interface have redefined in situ lead detection, thus they are still real-time, AI-powered, and support environmental safety.

In conclusion, the process of lead detection, which was initially done utilizing hefty laboratory techniques, has now moved to compact, smart sensors, which make it possible to do real-time monitoring. The detection method of each stage relies on the deficiencies of its predecessors, and therefore, key parameters like limit of detection (LOD), portability, repeatability, and response time have been improved. Yet, the problem of a perfect match between accuracy, cost-effectiveness, and scalability remains. In addition to that, the increasing link of lead pollution to anthropogenic activities such as fertilizer application and urban development will undeniably increase the need for continuous water quality monitoring. The review article documents the course and technical advancements in lead detection methods. The journey starts from the gravimetric and colorimetric techniques as early as time and proceeds to sensors integrated with nanomaterials, which are the most recent. It comprehensively covers the grounds, inventors, and milestones of all techniques and gives a comparative analysis of their pros and cons. This project is meant to identify current shortcomings and draft a future path along the sensor technologies that can solve and mitigate the problem of lead contamination in the global water systems by looking at previous successes.

## II. LITERATURE SURVEY

Lead ( $\text{Pb}^{2+}$ ) contamination in drinking water continues to pose serious risks to public health, driving extensive research into the development of reliable detection techniques. Over the past century, sensing technologies for lead have evolved significantly, beginning with foundational gravimetric methods and progressing through colorimetric and spectroscopic approaches, to the most recent innovations involving electrochemical and nanomaterial-enhanced platforms. Each method has contributed to the growing toolkit of analytical techniques, offering varied benefits in sensitivity, portability, cost, and field applicability.

One of the earliest techniques for lead quantification was the gravimetric method, introduced by Fay in 1907. This approach relied on the precipitation of lead from aqueous solutions using sulfate ions to form lead sulfate ( $\text{PbSO}_4$ ), which was subsequently filtered, dried, and weighed. Despite its simplicity and minimal equipment requirements, gravimetric analysis demanded strict control of conditions to ensure reproducibility. Its sensitivity was limited to milligram per liter (mg/L) levels, restricting its application to relatively high concentrations. Nonetheless, it remained the primary analytical standard for several decades and provided a critical baseline for more advanced methodologies. Colorimetric techniques introduced mid-century significantly improved accessibility and portability. The use of dithizone by Sandell and Kolthoff marked a key advancement. Dithizone forms colored chelate complexes with  $\text{Pb}^{2+}$  in organic solvents, producing red to violet hues measurable by eye or spectrophotometer. These methods enabled rapid screening of water samples and required minimal infrastructure, making them suitable for field testing. However, selectivity was a notable limitation, as cross-reactivity with other metal ions such as  $\text{Hg}^{2+}$  and  $\text{Cd}^{2+}$  often necessitated the use of masking agents. While not ideal for regulatory environments, colorimetry remains popular in simple lead test kits and educational settings.

The 1970s witnessed a major leap in lead detection sensitivity with the adoption of atomic absorption spectroscopy (AAS). In this technique, lead atoms in a gaseous state absorb radiation at a specific wavelength, with absorbance directly proportional to concentration. With the commercialization of AAS systems by companies like Perkinelmer, environmental testing became more accurate and widely standardized. AAS achieved detection limits in the parts-per-billion (ppb) range and remains a widely accepted method for compliance testing by agencies such as the EPA. In the 1980s, inductively coupled plasma mass spectrometry emerged as the most sensitive technique available. Developed by Houk, ICP-MS utilizes argon plasma to ionize elements, which are then sorted and quantified by mass-to-charge ratio. It provides multi-elemental analysis and ultra-trace detection down to parts-per-trillion (ppt), making it indispensable for detailed toxicological and environmental studies. While extremely accurate, the requirement for clean-room environments, expensive instrumentation, and skilled technicians has limited its field use.

To address the limitations of bulky spectroscopic equipment, the 1990s saw growing interest in electrochemical methods, particularly voltammetry. Differential pulse voltammetry (DPV) and anodic stripping voltammetry gained traction due to their ability to detect trace levels of heavy metals, including  $\text{Pb}^{2+}$ , at sub-ppb levels. These techniques measure changes in current as a function of applied voltage. They are highly sensitive when implemented with modified electrodes, such as those made of mercury, bismuth, or titanium dioxide composites. Their core mechanism involves preconcentrating  $\text{Pb}^{2+}$  onto the electrode surface and measuring current during its oxidation or reduction. Such approaches allow miniaturization, making them suitable for field-deployable sensors, though some degree of calibration and sample preparation is still required. Ahmed et al. introduced spectrophotometric methods using thiadiazole ligands that formed measurable colored complexes with  $\text{Pb}^{2+}$ . These systems offered better quantitative performance than classical colorimetric methods and allowed tuning of detection conditions, such as pH and masking agents, to minimize interference. Other studies optimized the method using flow-based analysis and UV-Vis detection, reaching detection limits as low as  $0.1 \mu\text{g/L}$ , which is compliant with WHO standards.

The late 2000s and 2010s brought a shift toward portable, real-time sensors using nanotechnology and electrochemical detection. Bliznakov et al. and Liu et al. developed electrochemical sensors based on carbon paste and glassy carbon electrodes, modified with chelating agents or nanoparticles. These platforms offered low-cost, scalable alternatives for field use, providing real-time results without the need for large equipment. Arabi et al. extended these systems to multi-ion detection and laid the groundwork for IoT-compatible water monitoring systems. Fluorescent detection also saw breakthroughs. Lu and Liu's DNAzyme-based fluorescence sensors offered unparalleled specificity by exploiting catalytic cleavage of DNA strands in the presence of  $\text{Pb}^{2+}$ . Further improvements with metal-organic frameworks (MOFs) and carbon dot-based probes enabled detection at nanomolar levels, with visual or fluorescent output. These sensors are label-free, operate in aqueous media, and show excellent selectivity in complex water samples, making them suitable for point-of-care diagnostics.

Nanomaterials have added a new dimension to lead detection. For example, aptamer-functionalized graphene-silver nanoparticle systems reported by Zhou et al. demonstrated strong binding affinity and measurable changes in conductivity upon  $\text{Pb}^{2+}$  interaction. Other work by Cui et al. involved the development of microwave-responsive nanoparticles embedded into microfluidic chips, allowing real-time and continuous monitoring. Integration with smartphones and nanocolorimetry platforms, as shown by Jiang et al., has enabled decentralized data acquisition and sharing.

The history of lead detection technologies reflects a broader trend in analytical science, from laboratory-dependent methods to point-of-need solutions. Gravimetric and early colorimetric techniques provided the first wave of detection protocols but were limited by sensitivity and manual operation. Spectroscopic methods such as AAS and ICP-MS revolutionized laboratory testing with high precision and low detection limits. Still, their utility in field applications remains limited due to cost and complexity. Electrochemical approaches, particularly voltammetry and modern impedance-based sensors, have bridged this gap by enabling high sensitivity in compact and affordable formats. Fluorescence-based sensors and nanomaterial-enhanced devices have enabled performance to reach ultra-trace levels, opening the door to smart sensing and smartphone compatibility. As this survey demonstrates, the future of lead detection in water lies in creating portable, selective, and user-friendly devices that maintain laboratory-grade accuracy. These innovations must align with real-world constraints like cost, power consumption, user training, and environmental interference, while adhering to international water quality guidelines. The evolution of lead sensing tools underscores the importance of multidisciplinary innovation in ensuring safe and accessible drinking water for all.

| Decade | Detection Method                           | Inventor / Author        | Principle                                                                                       |
|--------|--------------------------------------------|--------------------------|-------------------------------------------------------------------------------------------------|
| 1900s  | Gravimetric Analysis                       | Fred C. Fay              | Precipitation of $Pb^{2+}$ as $PbSO_4$ and weighing the dried residue                           |
| 1950s  | Colorimetry with Dithizone                 | Sandell & Kolthoff       | Dithizone forms a colored complex with $Pb^{2+}$ ions                                           |
| 1970s  | Atomic Absorption Spectroscopy (AAS)       | Perkin-Elmer Instruments | Pb atoms absorb characteristic light wavelengths when atomized                                  |
| 1980s  | ICP-MS (Mass Spectrometry)                 | Houk et al.              | Ionized Pb atoms are separated by mass/charge ratio in a mass spectrometer                      |
| 1990s  | Voltammetry (Electrochemical)              | Wang et al.              | $Pb^{2+}$ ions undergo redox reactions; the resulting current is proportional to concentration. |
| 2000s  | Spectrophotometry (Organic Ligands)        | Ahmed et al.             | Thiadiazole reacts with $Pb^{2+}$ to form a colored complex measured spectrally                 |
| 2008   | Electrochemical Sensor                     | Bliznakov et al.         | Modified electrodes show an electrical signal change when $Pb^{2+}$ binds                       |
| 2010s  | Fluorescence / DNAzyme Sensors             | Lu & Liu                 | DNAzymes cleave substrates upon $Pb^{2+}$ binding, causing fluorescence signal                  |
| 2017   | Polyaniline-Coated Sensor (Impedance)      | Alizadeh & Ganjali       | Conducting polymer's impedance changes when $Pb^{2+}$ binds to the surface                      |
| 2020s  | Nanomaterial-Based Electrochemical Sensors | Jie Zhou et al.          | Aptamer–AgNP/Graphene composites enhance $Pb^{2+}$ detection via signal amplification           |

Table I. Summary of Reported Methods for Lead ( $Pb^{2+}$ ) Detection

### III. CRITICAL ANALYSIS

A century of developing their methodologies shows that lead detection has gradually shifted from laboratory-intensive and expensive protocols to compact, field-capable sensing systems. Gravimetric and colorimetric metal ion analysis methods were a starting point, but their low sensitivity, manual performance, and reliance on skill meant they did not have much being developed in response to today's context. Spectroscopic methods have been produced by scientists with unmatched accuracy and very low detection limits that could ultimately be used for regulatory compliance, monitoring, and water chemical analyses at the forensic level. However, they are costly, require controlled situations, and the user needs expertise. Thus, spectroscopic methods would not have a place in the hands of most adults or within resource-limited regions. And while dramatic advances have been made, they remain laboratory-based and most costly methods that still do not have the rapid, point-of-need solutions needed for lead detection. Electrochemical methods, including voltammetry, have demonstrated important advancements toward portability, have become high-sensitivity methods that can be held in relatively small and inexpensive packages. Yet, electrochemical methods still encounter challenges associated with repeated and precise preparation of electrodes, required calibration, and controlled sample conditions, which could hinder non-expert users of these technologies. Like traditional colorimetry, spectrophotometric techniques have great improvements and high sensitivity, but they can still be susceptible to interference from other ions and may require basic laboratory tools to operate.

Recent advancements in nanomaterial-enhanced sensors, DNAzyme fluorescence platforms, and smartphone-enabled platforms point strongly toward the potential for democratized lead detection. These approaches embrace the positive characteristics that a portable, sensitive, and real-time reporting sensor could provide. However, there are still significant concerns with manufacturing complexity, noise susceptibility, and large-scale validation in real-world environments. From a human standpoint, contemporary technologies still approach lead detection as either an access lab or a trained technician in the field, which is a substantial gap from the day-to-day practice of a nontechnical person. Novel devices that can be manufactured in a low-cost, accessible, and user-friendly manner, validated concerning the manufacturer's restrictions, are a hard science need that I had anticipated missing. To address matters connected to science, we need to continue pursuing sensory and analytical refinements and refine the user interface, calibration-free operation, and low-maintenance requirements.

Therefore, while literature confirms the progression and development of lead detection science, there is a potential necessity for an accessible, low-cost, and user-centric sensing platform. This platform has the potential to allow communities an opportunity to consistently test their water quality habits without being beholden to laboratory infrastructure, ultimately moving forward with the ethos of social action for safe drinking water as a right.

#### IV. CONCLUSION

Lead contamination in our water bodies remains one of the most urgent environmental and public health demanding situations of the present-day generation. Its toxicological effects, even at trace concentrations, necessitate the development and implementation of dependable, sensitive, and handy detection technology. Over the past century, the development from classical gravimetric and colorimetric strategies to advanced spectrometric, electrochemical, and nanomaterial-based methods has not only displayed technological evolution but also a growing societal demand for accurate and discipline-deployable solutions. Each technique explored in this assessment brings specific strength. Gravimetric methods offered foundational accuracy; spectrophotometric and AAS systems delivered quantitative reliability; ICP-MS pushed the bounds of sensitivity; and electrochemical and fluorescence-primarily based sensors enabled portability and real-time monitoring. The emergence of nanomaterials as suitable platforms and integration with AI and cellphone technology marks a transformative segment, allowing decentralized and smart water fine control. Future studies must be conscious of combining high sensitivity with affordability, simplicity, and scalability. Emphasis should be placed on developing compact, battery-operated, and IoT-incorporated structures able to operate independently in remote areas. A holistic technique that unites scientific rigor with practical deployment strategies may be key to reaching sustainable and equitable water protection throughout the globe.

#### V. FUTURE SCOPE

Despite massive development in analytical and sensor-primarily based methods for lead ( $\text{Pb}^{2+}$ ) detection in water, several essential challenges persist. Traditional laboratory strategies consisting of atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS), at the same time as supplying extraordinary sensitivity and accuracy, are high-priced, non-portable, and require highly educated personnel. Conversely, emerging transportable strategies frequently compromise on selectivity, are afflicted by interference in complicated water matrices, or lack person-friendliness for non-professional stop-customers. These boundaries pose vast barriers to popular, habitual lead monitoring, mainly in low-resource or rural settings where infection dangers are frequently highest.

The future of water protection tracking lies in growing novel, low-price, user-centric sensors that are easy to set up, intuitive to function, and capable of correct on-site detection without the need for laboratory infrastructure. A key innovation direction is the engineering of nanomaterial-functionalized electrodes with excessive surface area and more advantageous selectivity for  $\text{Pb}^{2+}$  ions. Coupled with low-energy microelectronics, such sensors might be embedded in standalone devices or wearable modules for non-stop monitoring. In addition, AI-assisted signal processing and machine mastering-based totally calibration models can eliminate complex manual interpretation, offering real-time outcomes with computerized indicators. These fashions can also facilitate predictive analytics, permitting the government to music contamination developments and implement preemptive public health interventions. Importantly, future technology needs to pay attention to community-stage adoption. The ideal sensor could be compact, smartphone-like minded, and able to function across various water kinds (faucet, groundwater, commercial, and so on). This would empower individuals, even those without technical know-how, to affirm the safety of their consuming water, bridging the gap between scientific sophistication and everyday utility.

In conclusion, there may be a vast possibility and pressing need for inventing next-technology lead detection systems that might be accessible, adaptive, and sensitive. This technology ought to provide not only handiest access but also to democratize safe water access, ensuring that clean water is no longer a privilege but a universally upheld right.

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