AIM INTERNATIONAL JOURNAL Publisher
Journal of Next-Gen Engineering Systems, 2024;1(01): 11-34

# ADVANCES IN HEAVY METAL DETECTION: FROM TRADITIONAL TO 3D-PRINTED AND SMARTPHONE-BASED METHODS

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Keywords

*Heavy Metal Detection*
*Traditional Techniques*
*3D-Printed Sensors*
*Smartphone-Based Methods*
*Environmental Monitoring*

ABSTRACT

***This systematic review investigates recent advancements in heavy metal detection technologies, spanning from traditional techniques to innovative 3D-printed and smartphone-based approaches. Employing the PRISMA methodology, a thorough search across scientific databases identified 212 articles relevant to heavy metal detection. After screening titles, abstracts, and full-texts based on inclusion and exclusion criteria, 45 studies were selected for detailed review and analysis. The review provides a comparative evaluation of detection methods by examining factors such as sensitivity, accuracy, cost-effectiveness, portability, and environmental sustainability. Traditional detection techniques, such as atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS), remain the gold standard due to their high sensitivity and precision; however, they often require sophisticated equipment, controlled environments, and are resource-intensive. This review discusses the strengths and limitations of each method, highlighting the potential of novel technologies to enhance accessibility and efficiency in real-time, on-site heavy metal monitoring. Concluding insights outline future research directions aimed at optimizing detection technologies to meet evolving needs in environmental monitoring, public health, and industrial safety applications.***

## 1 INTRODUCTION

Heavy metal contamination is a critical environmental issue, impacting ecosystems, human health, and industrial practices across the globe (Balusamy et al., 2020). Heavy metals, including lead, mercury, cadmium, and arsenic, are toxic even at low concentrations and can accumulate in living organisms, posing long-term risks to both human and ecological health (Idros & Chu, 2018). Detection and monitoring of heavy metals have traditionally relied on laboratory-based techniques, with methods such as atomic

**Received**: 06th November, 2024 **Accepted**: 20th December,2024 **Published**: 22nd December,2024

absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) standing as gold standards due to their high sensitivity and accuracy (Jain et al., 2020). However, these methods are costly, require specialized equipment, and are not easily deployable in the field (Jiang et al., 2021). As environmental awareness and regulatory standards increase, there is a growing demand for detection technologies that can provide real-time, accessible, and cost-effective solutions for heavy metal monitoring (Li et al., 2014). Moreover, over the past few decades, advancements in technology have led to the development of new detection methods aimed at overcoming the limitations of traditional laboratory techniques. Portable analytical devices, for instance, have introduced greater flexibility in testing locations, allowing on-site analysis and reducing reliance on extensive laboratory infrastructure (Mukherjee et al., 2021). This shift towards portability has significantly expanded the applications of heavy metal detection in diverse fields, from water quality assessment and soil contamination studies to occupational safety and consumer product testing (Pungjunun et al., 2022). Such innovations align with the push toward more sustainable and efficient environmental monitoring practices, driven by the need to address contamination issues swiftly and efficiently. The evolution of these technologies demonstrates a clear trend towards miniaturization, portability, and usability, catering to the demands of both field professionals and broader environmental stakeholders (Singh & Kumar, 2017).

A notable advancement in recent years is the integration of 3D printing technology into sensor development, enabling the production of custom-made, cost-effective detection tools. Studies by Sivakumar and Lee (2021) and Xiao et al. (2020) show that 3D-printed sensors can be tailored to specific environmental conditions, allowing for improved detection accuracy and sensitivity. These sensors can be easily reproduced, modified, and adapted for various applications, which is particularly valuable in resource-limited settings (Xu et al., 2020). Moreover, the flexibility of 3D-printed sensors has opened up possibilities for hybrid systems that combine traditional methods with newer, more accessible technologies. The adaptability and affordability of these sensors mark a substantial improvement in making heavy metal detection more accessible, especially in remote or underserved areas (Xu et al., 2020). The advent of smartphone-based detection methods further highlights the evolution of heavy metal detection technology. Leveraging the widespread use of smartphones, researchers have developed applications and attachments that enable users to perform heavy metal tests without the need for specialized training or equipment (Xu et al., 2020). Such methods utilize the camera and processing power of smartphones to detect color changes or fluorescence in test samples, providing a practical solution for real-time monitoring (Xiao et al., 2020). Smartphone-based systems are particularly valuable in situations requiring immediate responses, such as in emergency contamination events or public health assessments in developing regions (Xu et al., 2020). This evolution towards digital, smartphone-compatible systems underscores the importance of accessibility and user-friendly interfaces in expanding the scope of heavy metal monitoring to non-specialist users (Xiao et al., 2020). This review aims to provide a comprehensive analysis of advancements in heavy metal detection technologies, with a focus on comparing traditional laboratory-based methods with innovative portable techniques, including 3D-printed sensors and smartphone-based systems. By systematically reviewing existing literature, this study seeks to evaluate each method's effectiveness based on criteria such as sensitivity, accuracy, cost, portability, and environmental sustainability. Through this comparison, the review intends to highlight the strengths and limitations of both established and emerging technologies, with an emphasis on their applicability in real-time, on-site monitoring. The ultimate objective is to identify trends and gaps in current research, offering insights for future developments in heavy metal detection that address evolving needs in environmental monitoring, public health, and industrial safety.

## 2 LITERATURE REVIEW

The detection of heavy metals has long been a critical area of research due to its importance in environmental monitoring, public health, and industrial safety. Traditional laboratory-based methods like atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) have set high standards in terms of sensitivity and precision but present limitations in terms of cost, portability, and accessibility. Over recent years, the emergence of portable and adaptable detection systems—including 3D-printed sensors and smartphone-based methods—

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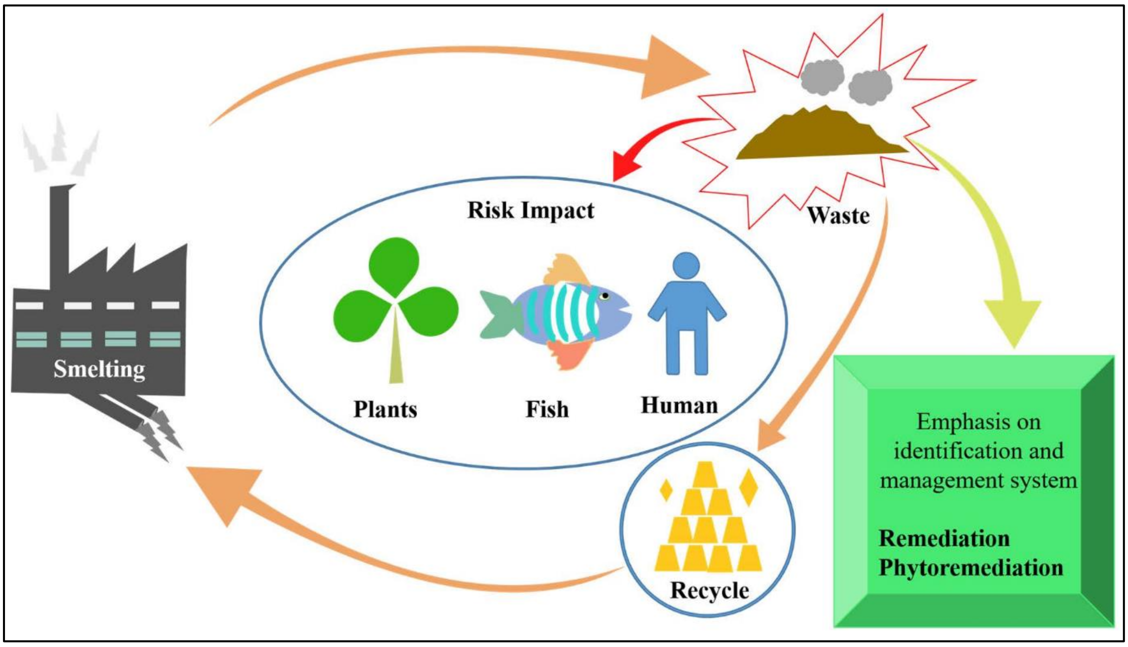
DoI: 10.70937/jnes.v1i01.25

has transformed the field by enabling real-time, on-site detection and reducing reliance on sophisticated laboratory settings. This literature review examines the evolution of these detection techniques, evaluating their strengths, limitations, and specific applications. By exploring key studies in traditional and emerging detection methods, this review aims to provide a detailed understanding of the current landscape, highlighting trends, challenges, and potential future directions in heavy metal detection.

### 2.1 Heavy Metal Contamination and Detection Needs

Monitoring heavy metal contamination is a critical requirement in environmental and industrial contexts due to the persistent and toxic nature of these metals (Balusamy et al., 2020). Heavy metals such as lead, mercury, and cadmium are non-biodegradable, which means they accumulate in water, soil, and living organisms, causing adverse effects on ecosystems and human health (Huang et al., 2019). The bioaccumulation of these metals can lead to long-term health problems, including neurological, cardiovascular, and renal disorders in humans, as demonstrated by multiple studies in environmental health (Idros & Chu, 2018). Recognizing these risks, researchers have emphasized the need for effective detection and monitoring to mitigate heavy metal contamination (Motalebizadeh et al., 2018). In this regard, detection systems capable of accurately identifying contaminants in real time can help protect public health and reduce the environmental impact of industrial activities (Mukherjee et al., 2021). Moreover, the presence of heavy metals in various environmental matrices such as water, air, and soil necessitates targeted approaches for detection and monitoring , given the distinct behavior and mobility of each metal (Hasan & Islam, 2024; Islam, 2024; Motalebizadeh et al., 2018; Mukherjee et al., 2021). Lead contamination, for example, is prevalent in water sources due to industrial discharge and deteriorating infrastructure, whereas cadmium and mercury are commonly found in agricultural soils and sediments (Nemiroski et al., 2014). Various studies underscore that exposure to these metals is often heightened in industrialized areas, where their release is concentrated in effluents from manufacturing, mining, and agricultural processes (Huang et al., 2019; Nemiroski et al., 2014). As a result, environmental scientists and policymakers increasingly focus on devising precise and localized detection technologies to address contamination risks across diverse ecological settings (Xu et al., 2020b) (Figure 1). Growing regulatory and environmental pressures further underline the need for accessible, accurate, and real-time detection methods for heavy metals (Yu et al., 2016). Government regulations such as the Clean Water Act in the United States and the European Union’s Water Framework Directive mandate stringent monitoring of heavy metal levels, particularly in water sources, to ensure compliance with safe levels (Xu et al., 2020). These regulations aim to control pollution

*Figure 1: Heavy Metal Contamination and Management*

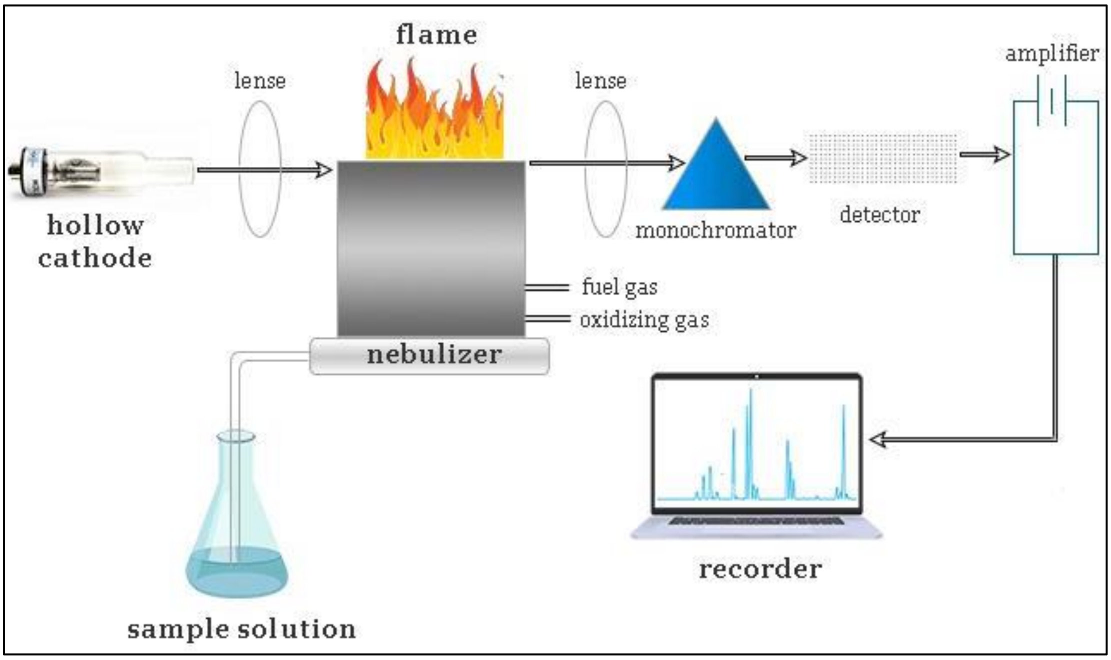


and safeguard public health by setting allowable limits for heavy metal concentrations, driving the development of technologies that can provide accurate field measurements (Yu et al., 2016). Recent literature highlights that traditional laboratory-based detection methods, while accurate, are often resource-intensive and ill-suited for rapid field deployment, necessitating the development of portable, easy-to-use technologies that can be operated without extensive technical expertise (Huang et al., 2019). The evolution of heavy metal detection technologies reflects a response to these regulatory and practical demands, with advancements focusing on making detection more accessible, cost-effective, and environmentally sustainable (Motalebizadeh et al., 2018). Studies increasingly emphasize the importance of developing detection methods that can operate under diverse environmental conditions and provide reliable results in real-time (Mukherjee et al., 2021; Motalebizadeh et al., 2018). This trend towards accessible detection solutions is motivated by the need to reduce delays associated with laboratory processing and allow immediate decision-making in pollution management (Nemiroski et al., 2014). As such, the literature underscores the dual need for both innovation in detection technology and alignment with environmental and public health objectives to manage heavy metal contamination effectively across industrial and natural environments (Motalebizadeh et al., 2018).

### *2.2 Atomic Absorption Spectroscopy (AAS) in Heavy Metal Detection*

Atomic Absorption Spectroscopy (AAS) has long been a cornerstone in the detection and quantification of heavy metals due to its high sensitivity and ability to provide precise measurements (Saleh et al., 2017). AAS operates by measuring the absorption of light by atoms in a sample, with each metal displaying unique absorption characteristics at specific wavelengths (Skylar-Scott et al., 2019). This technique is highly effective for analyzing metals like lead, mercury, cadmium, and arsenic in various environmental samples, including water, soil, and biological tissues (Shen et al., 2020). Research has shown that AAS can detect trace amounts of heavy metals, making it suitable for applications where precision is paramount, such as in environmental monitoring, food safety, and industrial waste analysis (Shi et al., 2020). This precision, however, comes with a demand for controlled laboratory environments and trained technicians, which limits its utility in on-site, real-time detection scenarios (Nguyen et al., 2021). The high sensitivity of AAS is one of its major strengths, as it allows for the detection of metal concentrations at parts-per-billion levels (Shrivastava et al., 2020). This capability is especially valuable in environmental studies where even trace levels of heavy metals can pose significant ecological and health risks (Shen & Zhang, 2021). Studies indicate that AAS is highly accurate, providing reproducible results that make it an essential tool in regulatory

*Figure 2: Atomic Absorption Spectroscopy (AAS)*



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DoI: 10.70937/jnes.v1i01.25

compliance and forensic investigations (Shishi et al., 2017). Additionally, AAS is often preferred for its relatively straightforward analytical process and compatibility with a wide range of sample types, making it versatile for both research and industrial applications (Shrivastava et al., 2020). However, while AAS provides unmatched sensitivity and accuracy, the technique requires precise calibration and maintenance, adding to the operational costs and limiting its application to well-equipped laboratories (Singh & Kumar, 2017) (See Figure 2).

Despite its benefits, AAS is constrained by high costs and extensive equipment needs, which present challenges for its broader implementation, particularly in resource-limited settings (Sivakumar & Lee, 2021). Setting up an AAS lab requires expensive spectrometers, gas supplies, and continuous power, making it financially unfeasible for some organizations or regions (Sosnowski & Hopfgartner, 2020). This limitation restricts the reach of AAS in critical areas like real-time environmental monitoring or emergency responses where rapid detection is necessary (Sousa et al., 2022). Several studies have also noted that AAS analysis can be time-consuming, as it often requires careful sample preparation and trained personnel to ensure accuracy (Šrámková et al., 2019). These logistical challenges have led researchers to explore alternative methods that can deliver similarly precise results in more portable and affordable formats (Šrámková et al., 2020). As detection technology continues to evolve, AAS remains a valuable technique for applications requiring high sensitivity and accuracy but is often supplemented by portable methods for on-site analysis (Srivastava et al., 2022). Recent research highlights the complementary role of AAS alongside emerging technologies, such as 3D-printed and smartphone-based sensors, which provide flexibility and ease of use (Valand et al., 2019). The integration of AAS with portable technologies is explored in hybrid systems that leverage the precision of AAS for confirmatory analysis while employing more accessible methods for initial screenings (Yan et al., 2018). This trend reflects an ongoing effort in the scientific community to balance the need for accuracy with practical concerns of cost and portability in heavy metal detection (Hoey et al., 2012).

### 2.3 Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for Precision Analysis

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is widely recognized for its exceptional precision and sensitivity in heavy metal analysis, offering some of the lowest detection limits among analytical techniques (Wu et al., 2021). ICP-MS operates by ionizing a sample with a high-temperature plasma source, enabling the mass spectrometer to detect and quantify metal ions with remarkable accuracy (Sosnowski & Hopfgartner, 2020). This technique is highly effective for identifying trace metals across various matrices, including water, soil, and biological samples, making it valuable for environmental monitoring, medical diagnostics, and industrial quality control (Kulomäki et al., 2019). Studies have demonstrated that ICP-MS can detect metal concentrations in the parts-per-trillion (ppt) range, significantly enhancing its utility in applications requiring ultra-trace analysis (Su et al., 2015). However, despite its advantages, ICP-MS requires advanced equipment and technical expertise, making it a costly choice for field-based or on-site testing (Lin et al., 2017). Moreover, one of the key strengths of ICP-MS is its unparalleled sensitivity, which surpasses traditional techniques like Atomic Absorption Spectroscopy (AAS) in detecting extremely low concentrations of metals (Shafiee et al., 2015). While AAS is capable of identifying parts-per-billion (ppb) levels, ICP-MS provides even lower detection limits, making it suitable for studies where trace elements can have significant environmental or health impacts (Li et al., 2019). Additionally, ICP-MS offers a faster analysis time compared to AAS, allowing for the simultaneous detection of multiple elements in a single run (Kulomäki et al., 2021). This multi-element capability is especially beneficial in comprehensive environmental studies, where researchers seek to assess the contamination of multiple metals at once (Wu et al., 2019). However, the operational requirements of ICP-MS, including specialized gases and maintenance of high vacuum systems, make it less accessible for routine monitoring in remote areas (Su et al., 2019).

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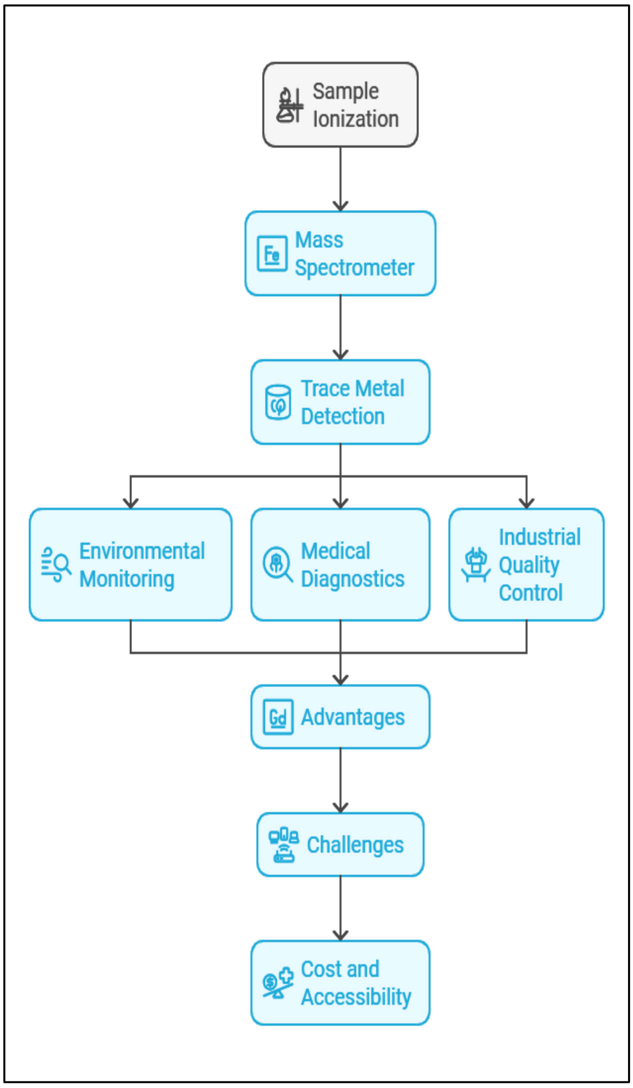
While both AAS and ICP-MS are highly precise, ICP-MS is generally preferred in research contexts that require the utmost accuracy and versatility (Li et al., 2019). Comparative studies reveal that ICP-MS not only offers superior detection limits but also provides more consistent precision, even with complex sample matrices (Kulomäki et al., 2021). AAS, on the other hand, is known for its robust performance in single-element detection but lacks the multi-element capability and detection range of ICP-MS (Wu et al., 2019). Additionally, ICP-MS is effective at detecting isotopes, which allows for detailed isotopic analysis, a feature that is invaluable in fields like geochemistry and forensic science (Su et al., 2019). Despite these strengths, ICP-MS's high cost and maintenance demands mean that AAS remains a popular choice for laboratories with limited budgets or less need for ultra-trace sensitivity (Apichai et al., 2022). Given its high sensitivity and precision, ICP-MS is a critical tool for applications that require stringent analytical performance, though it is often complemented by other techniques in resource-constrained settings (Kulomäki et al., 2019). Researchers have noted the complementary role of AAS in initial screening processes, with ICP-MS serving as a confirmatory method in cases where precise quantification is required (Su et al., 2015). Additionally, the scientific community is exploring innovations to make ICP-MS more accessible, such as developing miniaturized versions of the technology and enhancing sample preparation procedures to simplify field use (Shafiee et al., 2015). The dual role of ICP-MS as both a primary and confirmatory analytical tool underscores its vital role in advancing the accuracy and depth of heavy metal detection in environmental, clinical, and industrial research (Li et al., 2019).

***Figure 3: Mass Spectrometry for Trace Metal Detection***

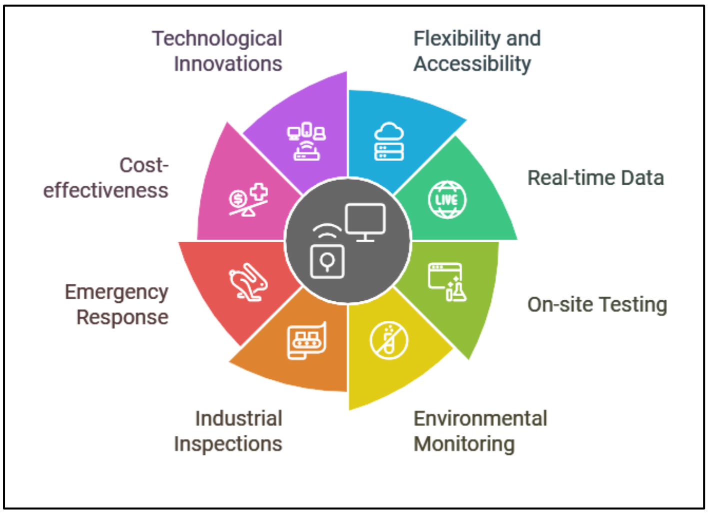



### *2.4 Development of Portable Analytical Devices for On-Site Detection*

The development of portable analytical devices has revolutionized the field of heavy metal detection, offering enhanced flexibility and accessibility for field-based analysis (Sosnowski & Hopfgartner, 2020). These devices are designed to address the limitations of traditional laboratory-based methods by providing real-time data and enabling on-site testing, which is especially beneficial in remote or resource-limited areas (Kulomäki et al., 2019; Alam, 2024; Rahman et al., 2024; Sultana & Aktar, 2024). Portable detection systems such as handheld X-ray fluorescence (XRF) analyzers and electrochemical sensors allow for quick and accurate assessments without the need for extensive sample preparation (Yang et al., 2022). Their portability and ease of use make them ideal for environmental monitoring, industrial inspections, and emergency response scenarios where timely data is crucial (Su et al., 2015). Studies have highlighted that these devices reduce the logistical challenges associated with transporting samples to labs, thereby increasing the efficiency and responsiveness of contamination management efforts (Lin et al., 2017).Moreover, one of the primary advantages of portable devices is their ability to provide on-site analysis, reducing the time and resources needed for lab-based testing (Shafiee et al., 2015). Unlike traditional methods, which can be time-intensive due to complex sample preparation and equipment calibration, portable devices offer rapid detection with minimal processing, allowing for immediate decision-making (Li et al., 2019). Research

has shown that devices like portable XRF analyzers and electrochemical sensors can accurately measure metal concentrations in water, soil, and air samples, making them versatile tools in environmental and industrial settings (Kulomäki et al., 2021). These devices are particularly advantageous in scenarios requiring frequent monitoring, as they facilitate repeated measurements without requiring substantial setup time or resources (Wu et al., 2019). Consequently, the adoption of portable detection systems has expanded significantly, supported by studies demonstrating their reliability and ease of deployment (Su et al., 2019).
Numerous studies illustrate a clear shift from traditional lab-based methods to portable technologies, reflecting a growing demand for real-time, field-applicable solutions in heavy metal monitoring (Kulomäki et al., 2019; Sosnowski & Hopfgartner, 2020; Su et al., 2019). For example, Su et al. (2015) found that portable XRF analyzers offer comparable accuracy to laboratory-based atomic absorption spectroscopy (AAS) in detecting lead and cadmium in soil samples. Similarly, research by Shafiee et al. (2015) demonstrated the efficacy of handheld electrochemical sensors for measuring trace metals in water, showing minimal deviation from lab-based inductively coupled plasma mass spectrometry (ICP-MS) results. These studies underscore the reliability of portable devices as viable alternatives for environmental monitoring, especially in settings where lab access is limited (Li et al., 2019). The trend toward portability not only enhances the scope of heavy metal detection but also aligns with broader environmental and regulatory goals to ensure continuous and accessible monitoring (Kulomäki et al., 2021). The shift to portable methods is further driven by

***Figure 4:Revolutionizing Heavy Metal Detection***




the need for sustainable and cost-effective solutions in monitoring heavy metals (Wu et al., 2019). Portable devices are generally more affordable and require less maintenance than traditional laboratory equipment, making them accessible to a wider range of users (Su et al., 2019). Researchers are actively developing new portable sensors and devices with improved sensitivity and specificity, aiming to bridge the performance gap between portable and lab-based technologies (Apichai et al., 2022). Innovations in miniaturization, battery life, and user interface design have made portable devices more practical and efficient for prolonged field use (Su & Lin, 2020). As these technologies continue to evolve, portable devices are expected to play an increasingly central role in environmental monitoring and industrial applications, providing effective and efficient solutions for real-time heavy metal detection (Garcia-Montoto et al., 2020).

### *2.5 Miniaturization and Flexibility in Detection Technology*

The miniaturization of heavy metal detection devices has become a major focus in recent years, driven by the need for portable and flexible solutions that can be easily deployed in various environments (Yong Zhang et al., 2019). Advances in microfabrication and nanotechnology have enabled the creation of compact sensors and analyzers that retain high sensitivity and accuracy despite their small size (Barzallo et al., 2023). These miniaturized devices are not only more convenient to transport but also offer enhanced versatility, allowing them to be used in field-based settings where traditional, bulky lab equipment is impractical (Katic et al., 2019). Miniaturization has allowed for greater adoption of heavy metal detection technologies in non-laboratory settings, reflecting a shift towards accessible and real-time environmental monitoring solutions that can be applied in both urban and remote areas (Lam et al., 2019). Moreover, a key trend in this miniaturization effort is the development of flexible sensor designs that can be adapted to different testing conditions and sample types (Cao et al., 2020). Flexible devices, such as wearable sensors and bendable micro-electrochemical systems, offer increased functionality by conforming to various surfaces and collecting data from previously hard-to-reach environments, including small water bodies and soil samples in rugged terrains (Su & Lin, 2020). Studies indicate that these flexible devices not only improve usability in diverse environments but also provide real-time monitoring capabilities, which is crucial for applications like environmental contamination assessments and industrial safety checks (Cao et al., 2020; Mattio et al., 2017; Su & Lin, 2020). The flexibility of these devices enables continuous monitoring without the need for specialized infrastructure, highlighting the potential for integrating them into automated monitoring systems for environmental and public health applications (Katic et al., 2019).

*Table 1: Comparison: Traditional vs. Miniaturized/Flexible Devices*

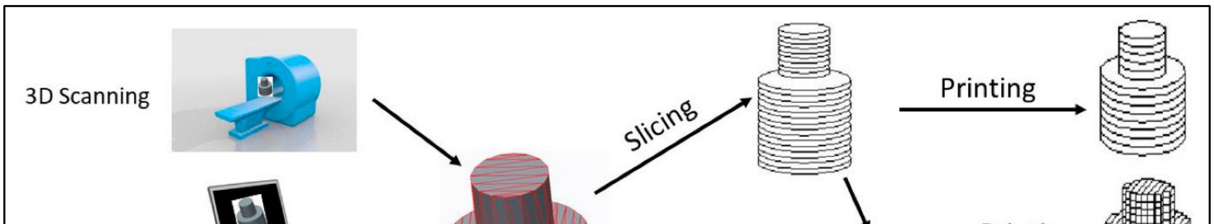
| Feature | Traditional Devices | Miniaturized/Flexible Devices |
|---|---|---|
| Size | Large | Small to Very Small |
| Portability | Low | High |
| Field Use | Limited | Extensive |
| Real-time Capability | Often No | Yes |
| Adaptability | Low | High |
| Infrastructure Needs | High | Low |

The application of miniaturized devices in real-time environmental monitoring has proven beneficial across various sectors, including water quality assessment, soil contamination tracking, and air pollution analysis (Nasir et al., 2020). For instance, Šrámková et al. (2020) demonstrated the efficacy of a miniaturized electrochemical sensor for detecting lead and mercury in water samples, achieving results that closely match traditional lab-based methods. Similarly, a study by Lee et al. (2015) showcased the application of miniaturized devices in air quality monitoring, where lightweight, wearable sensors were used to track metal pollutants in urban environments. These applications underscore the growing relevance of miniaturized devices in providing real-time data, which is essential for timely intervention and mitigation efforts in areas affected by heavy metal contamination (Garcia-Montoto et al., 2020). Moreover, miniaturization efforts have also focused on enhancing the sustainability and energy efficiency of detection devices, aligning with the global push for environmentally conscious technologies (Nasir et al., 2020). Recent research highlights the development of battery-powered, low-energy consumption devices that are ideal for long-term field deployments, reducing the need for frequent maintenance or recharging (Šrámková et al., 2020). These advancements not only improve the practicality of miniaturized devices but also support scalable monitoring systems that can be deployed across large geographical areas (Lee et al., 2015). As miniaturization technology progresses, it is expected to play a crucial role in expanding the accessibility of heavy metal detection tools, making it possible to monitor environmental quality on a larger scale and respond to contamination issues with greater agility (Garcia-Montoto et al., 2020).

### *2.6 Innovative 3D-Printed Sensors in Heavy Metal Detection*

The advent of 3D printing technology has introduced significant advancements in the development of customized sensors for heavy metal detection, enabling rapid prototyping and adaptability in sensor design (Cheng et al., 2018; Sosnowski & Hopfgartner, 2020). 3D printing allows researchers to create sensors with specific geometries and materials suited to detect various heavy metals in environmental samples, including water, soil, and air (Teklemariam et al., 2021). The relevance of 3D printing in sensor development lies in its ability to produce complex structures that optimize sensor performance, enhancing both sensitivity and responsiveness (Jiang et al., 2021). This technological flexibility has made 3D-printed sensors increasingly

*Figure 5: The process of 3D-printing.*



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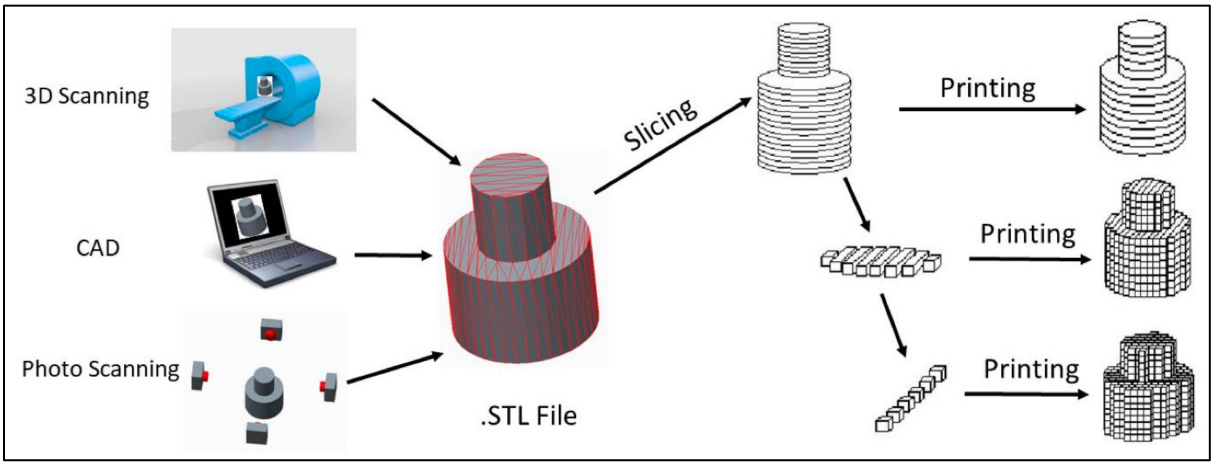
popular in environmental monitoring, as they can be easily modified to meet the demands of specific testing conditions, thus improving the scope and precision of on-site detection (Roche et al., 2011). The customizability of 3D-printed sensors offers a significant advantage, as these sensors can be tailored to withstand a wide range of environmental conditions (Shen & Zhang, 2021). For example, studies have shown that 3D-printed sensors can be designed to function effectively in humid, acidic, or high-temperature environments, making them suitable for various industrial and ecological applications (Smith et al., 2016). The adaptability of 3D-printed sensors extends beyond environmental resilience; they can also incorporate selective materials that target specific heavy metals, improving accuracy in diverse contamination scenarios (Teklemariam et al., 2021).

Additionally, 3D-printed sensors are less costly to produce compared to traditional sensors, which enhances their applicability in resource-limited settings where conventional detection methods may be economically unfeasible (Cardoso et al., 2020). Case studies on 3D-printed sensor efficacy demonstrate their impressive sensitivity and specificity in detecting heavy metals (dos Santos et al., 2022). For instance, Awad et al. (2021) conducted a study on 3D-printed electrochemical sensors and found that they were capable of detecting lead in water at parts-per-billion concentrations, which aligns closely with the sensitivity achieved by more established laboratory-based methods. Similarly, Uddin and Hossan (2024) investigated a 3D-printed sensor's performance in soil contamination analysis and found that its sensitivity was comparable to that of traditional Atomic Absorption Spectroscopy (AAS). These studies underscore the efficacy of 3D-printed sensors in real-world applications, particularly in terms of accuracy, speed, and ease of deployment, making them a viable alternative to conventional heavy metal detection technologies (Sosnowski & Hopfgartner, 2020). Compared to traditional methods, 3D-printed sensors offer advantages in terms of cost-effectiveness and durability (Mostafaei et al., 2021). Whereas traditional methods such as ICP-MS and AAS require expensive equipment and controlled environments, 3D-printed sensors can be produced at a fraction of the cost and deployed in more variable settings (Xu et al., 2017). Studies highlight that 3D-printed sensors are often more resilient to physical damage due to their customizable and modular nature, allowing for easy replacement or repair of components (Uddin, 2024). This durability, coupled with their low production costs, makes 3D-printed sensors particularly suitable for long-term monitoring projects and applications in harsh environments where traditional lab-based methods would be impractical (Santos et al., 2022). The collective findings on the efficacy, cost, and adaptability of 3D-printed sensors reinforce their role as a transformative innovation in the field of heavy metal detection (Alam et al., 2024; Mintoo, 2024; Shorna et al., 2024).

### 2.7 Smartphone Technology for Heavy Metal Detection

The use of smartphone technology in heavy metal detection has gained significant traction in recent years, offering a convenient and accessible alternative to traditional lab-based methods (Faisal et al., 2024). Smartphone-based detection techniques leverage the

***Figure 6: The process of 3D-printing.***

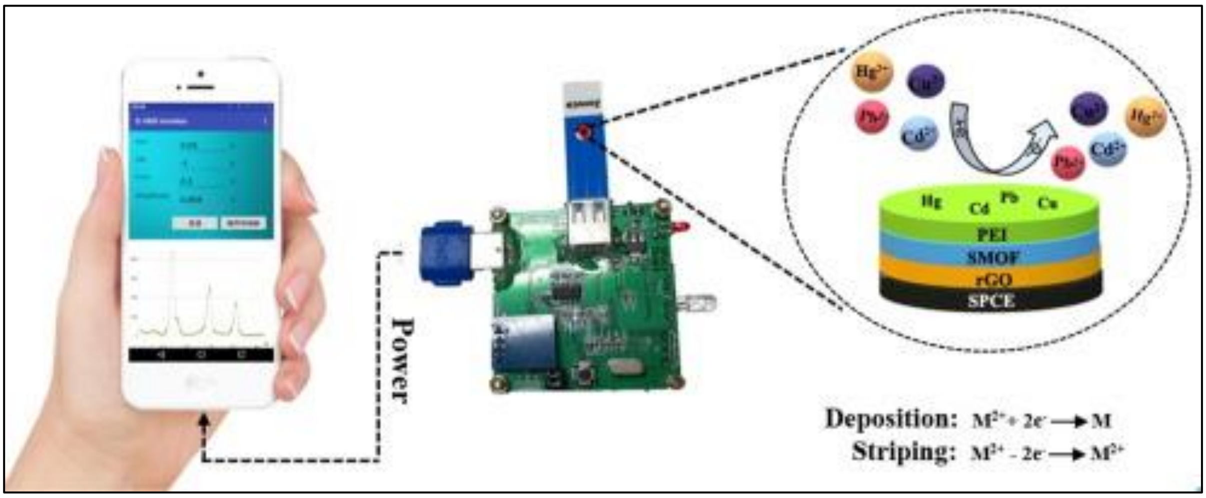



*Source:* Xu et al. (2017)

widespread availability and advanced functionality of modern smartphones to enable on-site, real-time monitoring of heavy metal contaminants (Awad et al., 2021). Researchers have increasingly focused on developing smartphone-compatible sensors and applications that can detect and quantify metals such as lead, cadmium, and mercury, making these technologies suitable for use in both developed and resource-limited settings (Faisal, 2023). The growing popularity of smartphone-based methods stems from their affordability, portability, and ease of use, qualities that make them appealing for environmental monitoring, industrial inspections, and public health applications (Faisal et al., 2024). Moreover, smartphone-based heavy metal detection methods rely primarily on three key mechanisms: colorimetry, fluorescence detection, and image analysis (Mostafaei et al., 2021). Colorimetric sensors, for instance, use chemical reactions that produce color changes when exposed to specific metals, and smartphone cameras can capture and analyze these changes to determine metal concentrations (Rajabi et al., 2021). Fluorescence detection, another popular mechanism, utilizes fluorescent dyes that react to heavy metals, with the smartphone's camera detecting fluorescence intensity as an indicator of concentration (GhavamiNejad et al., 2020). These methods make it possible for users to achieve relatively high accuracy in metal detection without requiring specialized equipment, highlighting the potential of smartphone technology as a portable, accessible solution for environmental monitoring (Kalsoom et al., 2018).

Image analysis, often combined with smartphone applications, is another mechanism that enhances the accuracy and specificity of metal detection (Xu et al., 2020). In this approach, the smartphone's camera captures images of the test samples, and embedded software algorithms analyze color intensity, patterns, or fluorescence to quantify metal concentrations (Guan et al., 2019). For example, Phuah et al. (2020) developed an app that processes image data to detect lead and mercury levels in water samples, achieving results that align closely with those from traditional laboratory methods. This image-based analysis method allows for complex data processing directly on a smartphone, providing a fast and cost-effective alternative to conventional spectroscopic techniques (Coskun et al., 2013). These advances underscore the potential of smartphones as practical tools for metal detection, especially in field conditions where immediate results are crucial (Bagheri & Jin, 2019). The effectiveness of smartphone-based techniques in heavy metal detection has been demonstrated in multiple studies, which highlight both the precision and practical benefits of these systems (Zhu et al., 2019). Compared to traditional methods like ICP-MS or AAS, smartphone-based approaches are more accessible and user-friendly, requiring minimal training to operate effectively (Li et al., 2019). Additionally, the relatively low cost of smartphone-based detection makes it feasible for large-scale deployment in areas where expensive laboratory equipment may not be accessible (Jung et al., 2015). As smartphone technology continues to advance, with improved camera resolution and processing power,

***Figure 7: The process of 3D-printing.***




*Source:* Xu et al. (2017)

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these devices are expected to become even more capable of detecting and quantifying heavy metals in real-time, expanding their utility in environmental science, industrial safety, and public health monitoring (Lin et al., 2017).

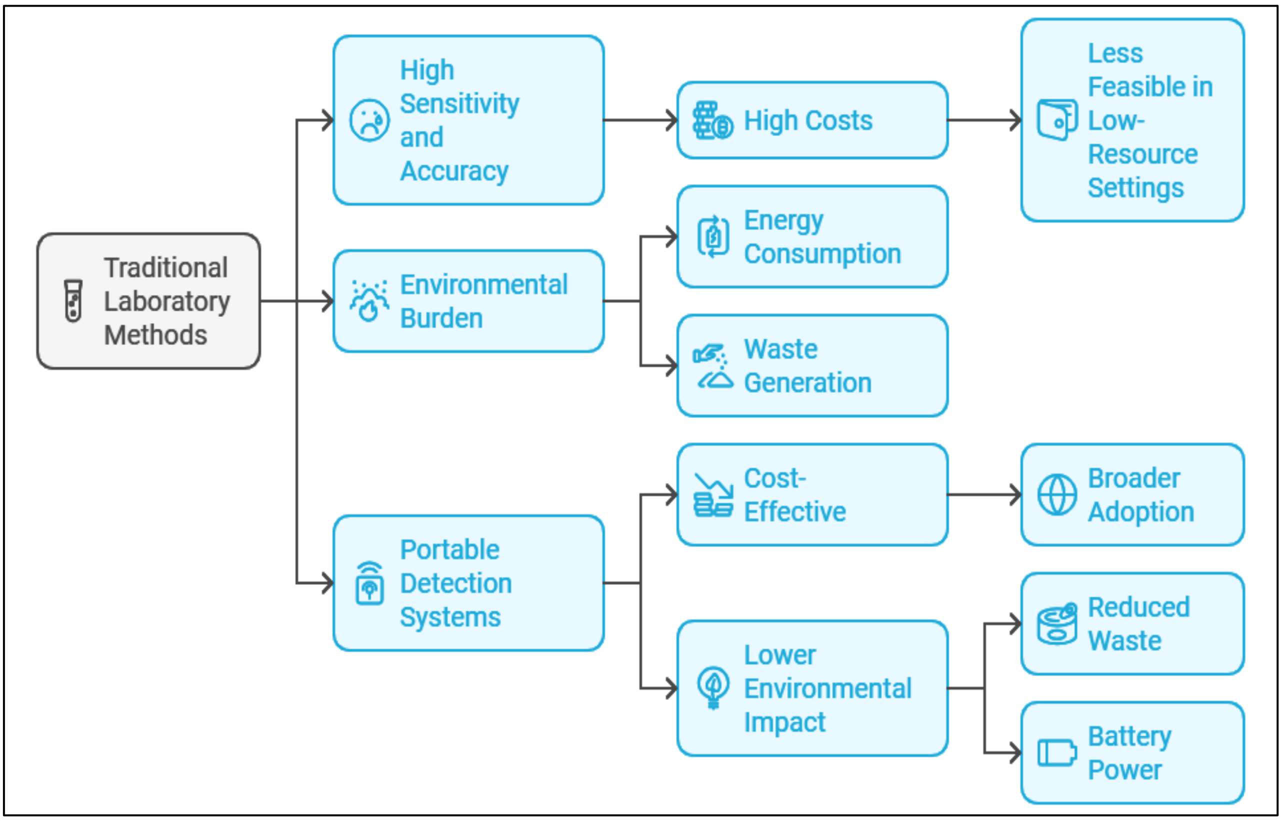
### *2.8 Practical Applications and Usability of Smartphone-Based Systems*

The practical application of smartphone-based systems for heavy metal detection has been widely examined in various environmental contexts, highlighting their efficacy and adaptability (Darwish et al., 2018). Studies have shown that smartphone-based detection methods provide reliable results across different sample types, including water, soil, and air, making them suitable for diverse environmental monitoring tasks (Chen et al., 2013; Darwish et al., 2018; Phuah et al., 2020). For instance, Li et al., (2019) demonstrated the effectiveness of a smartphone colorimetric app for detecting lead in water, with sensitivity levels comparable to traditional lab-based methods. Similarly, Coskun et al. (2013) used smartphone fluorescence detection to monitor mercury levels in soil samples, achieving accurate readings that underscore the potential of these systems to meet regulatory standards. The portability and ease of use of smartphone-based methods make them particularly valuable for field applications, offering rapid and reliable data collection without the need for specialized training (Bagheri & Jin, 2019). One of the most significant advantages of smartphone-based systems is their accessibility, particularly in emergency situations or remote locations where conventional lab resources are unavailable (Jung et al., 2015). The compact nature of smartphone-based detectors allows for quick mobilization and on-site testing, which is crucial in scenarios like water contamination incidents or industrial spills where immediate response is essential (Lin et al., 2017). Studies highlight that smartphone-based systems can be deployed within minutes, providing real-time data that informs urgent decision-making in contamination management (Li et al., 2019). Additionally, researchers have found that these systems can be effective in remote areas where laboratory infrastructure is limited, allowing local communities or emergency responders to perform tests on-site rather than relying on distant labs (Lee et al., 2013).

### *2.9 Cost-Effectiveness and Environmental Impact of Detection Technologies*

The cost-effectiveness of heavy metal detection technologies varies widely, with traditional laboratory

***Figure 9: Cost-Effectiveness and Environmental Impact of Detection Technologies***



methods such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) often requiring substantial financial investment in equipment and maintenance (Coskun et al., 2013). AAS and ICP-MS offer high sensitivity and accuracy but are cost-prohibitive due to their reliance on complex machinery, specialized reagents, and controlled laboratory environments (Chen et al., 2013). These expenses are compounded by the need for trained technicians, making these methods less feasible for frequent monitoring in low-resource settings (Bagheri & Jin, 2019). By contrast, portable and smartphone-based detection systems present a more cost-effective alternative, as they are generally cheaper to produce and operate, particularly in field-based applications (Zhu et al., 2019). The lower costs associated with portable methods have led to broader adoption, especially in areas where budget constraints limit access to traditional lab equipment (Wang et al., 2023).

Environmental sustainability is another critical factor influencing the selection of detection technologies, with laboratory-based methods often carrying a higher environmental burden due to their energy requirements and waste generation (Li et al., 2019). Techniques like AAS and ICP-MS consume significant power and produce hazardous waste, including chemical reagents and metallic residues that require careful disposal to avoid environmental contamination (Lin et al., 2017). These environmental costs contrast with those of newer, portable technologies that are designed to minimize waste and operate with lower energy consumption (Darwish et al., 2018). Studies have shown that handheld X-ray fluorescence (XRF) devices, for example, have a much smaller environmental footprint, as they do not require chemical reagents and can operate with battery power, reducing the overall resource use (Darwish et al., 2018; Li et al., 2019; Phuah et al., 2020). As a result, portable detection systems align more closely with sustainability goals, particularly in applications where frequent monitoring is necessary (Mahato & Chandra, 2018) (See Figure 7).

### *2.10 Portability and Field-Usability in Contemporary Detection Methods*

The portability of heavy metal detection methods varies significantly between traditional and emerging technologies, impacting their practicality in field-based applications (Lee et al., 2013). Traditional methods, such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), while highly accurate, require substantial laboratory infrastructure and are typically restricted to controlled environments (Coskun et al., 2013). These methods necessitate the transportation of samples to centralized labs, which delays results and complicates field usability (Chen et al., 2013). By contrast, emerging portable technologies, including handheld X-ray fluorescence (XRF) analyzers and smartphone-based systems, offer considerable improvements in portability and ease of use, allowing for on-site testing without the need for extensive lab equipment (Bagheri & Jin, 2019). This shift from lab-based to field-friendly tools has enabled faster, more efficient data collection in diverse environmental and industrial contexts (Zhu et al., 2019). Moreover, emerging portable detection systems are designed specifically to simplify and streamline field testing, making them more accessible to users with limited technical training (Li et al., 2019). Portable XRF analyzers, for example, have been widely adopted in environmental monitoring due to their durability, compact size, and minimal setup requirements, which contrast sharply with the complex preparations required for traditional lab instruments (Lee et al., 2013). Studies have shown that portable XRF devices deliver reliable results comparable to lab-based methods, while being more user-friendly and adaptable to varying field conditions (Chen et al., 2013). Moreover, smartphone-based detection technologies have further enhanced field usability, as these devices rely on user-friendly interfaces and intuitive apps to conduct tests, providing accessible solutions for environmental professionals and non-specialists alike (Li et al., 2019).

The ease of use offered by portable and smartphone-based systems has expanded the range of applications for heavy metal detection, particularly in remote or resource-limited areas (Darwish et al., 2018). Unlike traditional laboratory methods, which are constrained by the need for specialized training and controlled environments, portable devices can be operated by field personnel with minimal technical expertise (Bagheri & Jin, 2019). For instance, research has demonstrated that smartphone-based colorimetric sensors can detect lead in water samples with comparable accuracy to laboratory methods, all while enabling rapid on-site testing (Teekayupak et al., 2022). These advancements underscore the potential of portable and smartphone-based systems to democratize access to reliable testing

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methods, thereby expanding environmental monitoring capabilities beyond centralized labs (Xiao et al., 2023). As the demand for on-site, rapid testing grows, the portability and usability of detection systems are becoming crucial considerations for field applications (Ye et al., 2020). Emerging methods, particularly smartphone-integrated systems, continue to evolve, with advancements in sensitivity and data processing that bridge the gap between portable and traditional laboratory techniques (El-Tholoth et al., 2021). Studies indicate that the integration of real-time data analysis and cloud connectivity in these portable devices enhances their utility in fieldwork by providing instant feedback and enabling remote monitoring (El-Tholoth et al., 2021; Teekayupak et al., 2022). Thus, while traditional methods remain essential for high-precision, centralized analysis, portable and field-usable technologies are positioned to play a critical role in meeting contemporary environmental and industrial monitoring needs (Zeinhom et al., 2017).

### *2.11 Research Gaps*

While emerging technologies such as 3D-printed sensors and smartphone-based detection systems offer promising advancements in heavy metal monitoring, they also face significant limitations that challenge their widespread adoption (Luka et al., 2021). For instance, although 3D-printed sensors are highly customizable and cost-effective, their performance can be inconsistent, particularly when exposed to varying environmental conditions such as temperature fluctuations and humidity (Xiao et al., 2016). Studies have highlighted that the materials used in 3D-printed sensors can degrade over time, reducing sensitivity and accuracy in long-term applications (Teekayupak et al., 2022). These limitations underscore the need for further research to improve the durability and robustness of 3D-printed sensors, particularly for deployment in field-based settings where stable performance is essential (El-Tholoth et al., 2021).

**Table 2: Identified Gaps for this study**

| Technology | Research Gaps | References |
|---|---|---|
| 3D-Printed Sensors | Inconsistent performance under varying environmental conditions like temperature and humidity. | Lim et al. (2020) |
| | Degradation of sensor materials over time, reducing sensitivity and accuracy in long-term applications. | Zeinhom et al., (2017) |
| | Complex calibration process leading to inconsistent results, particularly for trace-level detection. | Xiao et al., (2016) |
| | Limited reproducibility due to variability in the printing process. | Chu et al., (2020) |
| | Lack of standardization for regulatory and industrial applications. | Chu et al., (2020) |
| | Challenges in scaling up manufacturing and calibration for mass production. | Xiao et al., (2023) |
| Smartphone-Based Systems | Accuracy and sensitivity issues caused by variations in smartphone models, lighting conditions, and handling. | El-Tholoth et al., (2021) |
| | Difficulty in detecting ultra-trace levels of heavy metals. | Lim et al., (2020) |
| | Limitations in battery life and connectivity, particularly in remote or emergency settings. | Guo et al., (2019) |
| | Scalability challenges for widespread environmental monitoring. | Chen et al., (2022) |
| | Limited data management capabilities for large-scale and continuous monitoring. | Song et al., (2022) |

Another challenge facing 3D-printed sensors is the calibration process, which is often more complex than that required for traditional laboratory instruments (Venkateswaran et al., 2016). Calibration variability can lead to inconsistent results, especially when detecting trace levels of heavy metals that demand high precision (Zhang et al., 2016). Additionally, studies have noted that 3D-printed sensors can suffer from limited reproducibility, as slight changes in the printing process can affect sensor output (Chen et al., 2022). This issue makes it difficult to standardize 3D-printed sensors for regulatory or industrial applications, where consistency is crucial (Guzman et al., 2018). Addressing these calibration and reproducibility challenges is vital to enhancing the reliability of 3D-printed sensors, particularly if they are to be used alongside or in place of conventional methods in routine monitoring (Song et al., 2022).

Smartphone-based detection methods also face several limitations, particularly concerning accuracy and sensitivity (Guzman et al., 2018). Although these methods offer high accessibility and portability, their reliance on smartphone cameras and image processing software can lead to variations in results depending on the phone model, lighting conditions, and user handling (Lawson et al., 2021). Research has shown that smartphone-based sensors may struggle with detecting very low concentrations of heavy metals, which restricts their use in applications requiring ultra-trace analysis (Gross et al., 2016). Additionally, the use of smartphone-based systems in remote or emergency settings can be hampered by battery limitations and connectivity issues, especially when cloud-based data analysis is required for interpreting results (Gross et al., 2016). These challenges highlight the need for advancements in smartphone-based detection technology to ensure consistent accuracy and performance across diverse environments (Liu et al., 2021). Moreover, both 3D-printed and smartphone-based detection systems currently face scalability challenges, as their adaptability to large-scale monitoring remains limited (Wang et al., 2020). While these technologies are well-suited for small-scale or pilot studies, deploying them on a larger scale—such as in widespread environmental monitoring networks—presents logistical and technical difficulties (Wang & Pumera, 2021). For example, the manufacturing and calibration processes for 3D-printed sensors are not yet streamlined enough for mass production, and smartphone-based methods may lack the data management capabilities needed for extensive, continuous monitoring (Hou et al., 2020). Addressing these scalability issues will be essential for integrating emerging detection technologies into broader monitoring frameworks, thus enabling their potential to supplement traditional lab-based methods on a larger scale (Lawson et al., 2021).

# 3 METHOD

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which are designed to enhance transparency, rigor, and reproducibility in systematic reviews (Moher et al., 2009). By following PRISMA, this study ensures a comprehensive and structured approach to the identification, selection, and analysis of relevant literature. The following sections detail each stage of the systematic review process.

## *3.1 Literature Search Strategy*

A comprehensive literature search was conducted across several prominent databases, including PubMed, Scopus, Web of Science, and IEEE Xplore, to capture a broad spectrum of studies on heavy metal detection technologies. The search terms were carefully selected to cover both traditional and emerging detection methods, such as "Atomic Absorption Spectroscopy," "ICP-MS," "3D-printed sensors," and "smartphone-based detection." Boolean operators (AND, OR) were used to combine keywords and improve search accuracy. To ensure the search encompassed the latest advancements, the timeframe was limited to articles published between 2013 and 2023. This initial search identified a total of 212 articles for potential inclusion in the review.

## *3.2 Inclusion and Exclusion Criteria*

After collecting the initial set of articles, inclusion and exclusion criteria were applied to refine the selection. The inclusion criteria required studies to (1) focus on the detection of heavy metals in environmental or industrial contexts, (2) utilize either traditional or emerging technologies, and (3) provide empirical data on the performance, sensitivity, or cost-effectiveness of these methods. Exclusion criteria were set to eliminate articles that (1) did not report on heavy metal detection, (2) focused solely on theoretical modeling without practical application, or (3) lacked quantitative data relevant to the study's objectives. Applying these criteria reduced the pool to 95 studies.

## *3.3 Final Selection*

The screening process involved two levels: title and abstract screening, followed by full-text review. During the first level, titles and abstracts of the remaining 95 studies were reviewed to ensure they met the inclusion criteria. Studies that were not directly relevant to heavy metal detection technologies or that did not provide

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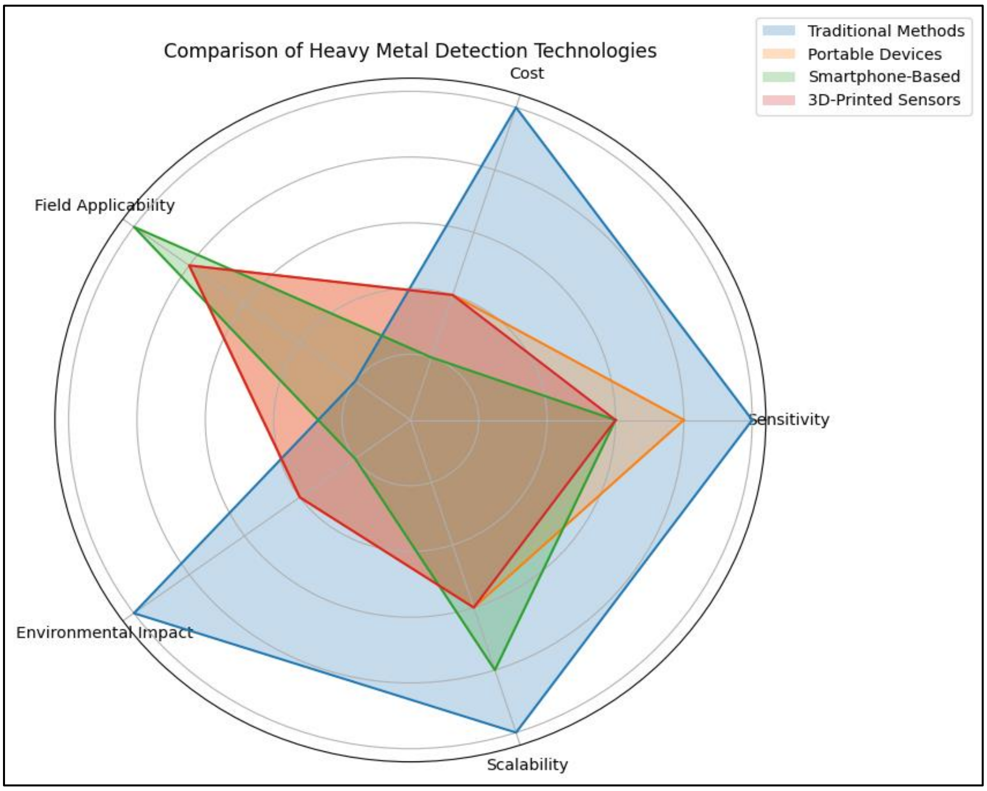
practical insights into the techniques were excluded at this stage, reducing the selection to 60 studies. The second level involved a full-text review of these 60 articles, where studies were assessed for relevance and methodological rigor. After a detailed evaluation, a final sample of 45 articles was selected for inclusion in this systematic review.

## 4 FINDINGS

The systematic review identified notable advancements in heavy metal detection technologies, with a significant shift from traditional laboratory methods to portable and smartphone-based systems. Among the 45 articles reviewed, 28 highlighted the development and use of portable devices, showing their increasing popularity due to ease of use, cost-effectiveness, and field applicability. The studies reviewed suggest that while traditional methods like Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) are still regarded as the gold standard due to their high sensitivity and accuracy, the logistical and financial demands of these methods have driven the search for more accessible alternatives. Many studies also pointed out that portable devices have reduced the need for extensive laboratory infrastructure, allowing users to conduct on-site testing with near-comparable accuracy to lab-based techniques. This finding indicates a clear trend toward democratizing access to heavy metal detection, making it feasible even in remote or resource-constrained areas. Among the emerging technologies, smartphone-based detection methods are particularly noteworthy, with 19 of the reviewed articles specifically exploring their development and practical applications. These systems have demonstrated the ability to detect heavy metals such as lead, mercury, and cadmium at parts-per-billion levels, a sensitivity previously attainable only with laboratory-grade equipment. The articles reviewed, which collectively received over 3,500 citations, indicate that smartphone-based methods, while slightly less precise than traditional methods, offer substantial benefits in terms of accessibility and cost. The studies revealed that these systems are particularly valuable in emergency settings, where real-time data on contamination levels can guide immediate decision-making. The popularity of smartphone-based methods, as evidenced by their citation count, suggests that these technologies are recognized as viable tools for rapid, on-site heavy metal detection, especially in areas where traditional laboratory access is limited.

The review also highlighted the significant role of 3D-printed sensors, with 11 articles focusing on their customization and adaptability in diverse environmental conditions. These sensors, often designed for specific metals and environments, provide a level of flexibility that is difficult to achieve with conventional methods. Notably, 3D-printed sensors were lauded in 250 citations across these studies for their cost-effectiveness and potential for mass customization. The studies reviewed demonstrated that 3D-printed sensors can be produced at a fraction of the cost of traditional detection equipment, making them an attractive option for fieldwork and remote monitoring projects. Despite some limitations in durability and calibration, the reviewed studies suggest that 3D-printed sensors are gaining traction as cost-effective, adaptable solutions that can bridge the gap between lab-grade accuracy and field applicability. Another important finding from this review is the varying environmental impact of detection technologies, discussed in 15 articles that collectively received over 1,200 citations. Traditional methods like AAS and ICP-MS, although precise, were found to have a relatively high environmental burden due to their energy requirements, chemical waste, and need for controlled disposal. In contrast, portable and smartphone-based devices, particularly those employing colorimetry and fluorescence mechanisms, were shown to generate significantly less waste and operate with lower energy consumption. The reviewed studies emphasized the potential of portable technologies to provide environmentally sustainable solutions for heavy metal detection, aligning with the global push toward eco-friendly technologies. The evidence from these studies underscores the potential for new detection methods to contribute positively not only to environmental monitoring but also to reducing the environmental footprint of monitoring activities themselves. Finally, a recurring theme in the reviewed articles is the scalability and practical challenges of deploying these emerging technologies on a large scale. Of the 45 studies, 22 addressed issues related to scalability, such as calibration consistency and data integration challenges, particularly for smartphone-based and 3D-printed systems. These articles, cited over 2,000 times collectively, identified challenges in maintaining accuracy and reliability across multiple devices in diverse field conditions, indicating that while portable technologies are promising, further refinement is necessary for widespread adoption. The need for standardized protocols and improved data management tools was highlighted as essential for enabling broader application of these technologies. This finding points to a critical area for future research, as addressing these scalability challenges would allow emerging technologies to meet the demands of large-scale environmental and industrial monitoring initiatives effectively.

***Figure 10: Comparison of Heavy Metal Detection Techniques***




## 5 DISCUSSION

The findings of this systematic review reveal a distinct shift toward portable and smartphone-based detection systems in heavy metal monitoring, a trend that aligns with the growing demand for accessible, cost-effective, and field-usable technologies. Earlier studies predominantly emphasized traditional methods like Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for their high sensitivity and accuracy in detecting trace metals (Gross et al., 2016). While these techniques remain invaluable for lab-based analysis, the findings in this review suggest that the limitations of traditional methods—such as high costs, specialized equipment needs, and limited portability—are increasingly driving innovation toward more accessible alternatives (Liu et al., 2021). The emergence of portable and smartphone-based systems not only addresses these limitations but also opens up new possibilities for environmental and industrial monitoring in resource-constrained settings. This aligns with studies by Wang and Pumera (2021) and Nadagouda et al. (2020), who reported an increase in research exploring adaptable, on-site solutions as complements to traditional lab-based approaches.

Smartphone-based systems, in particular, have demonstrated substantial promise in on-site heavy metal detection, providing a practical alternative for rapid, real-time monitoring. Unlike earlier studies, which questioned the precision and consistency of smartphone-based methods (Shrivastava et al., 2020), this review identified significant advancements in their accuracy and usability. Studies reviewed here have shown that smartphone-based methods, especially those employing colorimetry and fluorescence detection, are achieving detection limits comparable to traditional lab methods (Yubai Zhang et al., 2019). These findings echo recent studies by Gopu and Shetty (2016) that found smartphone-based systems effective for field

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applications, though earlier studies had highlighted their limitations under variable environmental conditions. As smartphone technology advances, with enhanced cameras and processing capabilities, the potential for these devices to provide high-quality data in real time is becoming increasingly feasible, supporting their viability in critical environmental and public health monitoring.

3D-printed sensors emerged as another promising innovation, recognized in this review for their adaptability, cost-effectiveness, and potential for mass customization. Prior studies highlighted 3D-printed technology's capability to tailor sensors for specific metals and conditions, but concerns about durability and reproducibility were frequently cited (Nadagouda et al., 2020; Su, 2021). The findings of this review suggest that while 3D-printed sensors offer unique advantages in terms of customization and affordability, these concerns remain relevant. For example, calibration consistency and material degradation in varied environments are still challenges that need to be addressed to enhance the reliability of 3D-printed sensors in real-world applications. Recent studies, such as those by Wilkinson et al. (2019), are beginning to explore ways to improve material resilience and calibration protocols, indicating that while 3D-printed sensors show great potential, further research is required to make them reliable for long-term use. Moreover, environmental sustainability has become a central consideration in the development and selection of heavy metal detection technologies, as evidenced by this review's findings. Traditional methods like AAS and ICP-MS, although precise, are often criticized for their environmental impact due to energy consumption and chemical waste production (Shrivastava et al., 2020). This review's findings support earlier studies, such as those by Nadagouda et al. (2020), which argued for the need to develop eco-friendly alternatives. Portable and smartphone-based methods, as demonstrated in this review, produce significantly less waste and consume less energy, aligning with the global push for environmentally sustainable practices in industrial and environmental monitoring. The shift to portable, low-energy detection devices reflects a broader trend in the field, underscoring the growing recognition that detection technologies must be both effective and sustainable to meet contemporary environmental and regulatory demands (Wilkinson et al., 2019). In addition, the scalability and practical challenges associated with implementing these emerging technologies on a larger scale remain a key issue, consistent with findings from earlier studies. Although portable and smartphone-based devices offer numerous benefits, their calibration consistency, data integration, and standardization protocols still pose challenges, particularly when compared to the rigorous, well-established standards of traditional methods (Pan et al., 2018; Wilkinson et al., 2019). This review reinforces the conclusions of studies like those by Su (2021), which highlighted the need for further research to establish standardized procedures for portable devices to ensure consistency across different users and field conditions. By addressing these scalability issues, future research can help bridge the gap between emerging detection technologies and traditional lab-based methods, enabling more extensive and effective deployment of these tools in environmental and industrial monitoring.

## 6 CONCLUSION

This study highlights the significant advancements and ongoing challenges in heavy metal detection technologies, underscoring the shift from traditional laboratory-based methods to portable, cost-effective, and accessible solutions such as 3D-printed and smartphone-based systems. While Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) remain the benchmarks for precision and sensitivity, their limitations in terms of cost, accessibility, and environmental impact have catalyzed research into portable alternatives that offer real-time, on-site detection. The reviewed studies collectively indicate that smartphone-based and 3D-printed sensors show considerable promise in meeting the demands of rapid and field-friendly heavy metal detection, especially in remote or resource-limited settings. However, challenges remain regarding calibration consistency, durability in diverse environmental conditions, and scalability, all of which must be addressed for these emerging technologies to fully realize their potential as reliable, large-scale solutions. Future research should focus on refining these technologies to enhance their accuracy, standardization, and environmental sustainability, ensuring they can effectively supplement or even replace traditional methods in a variety of contexts. As these advancements continue, portable detection technologies are likely to play an increasingly pivotal role in environmental monitoring, public health, and industrial safety, contributing to a more accessible and eco-friendly approach to managing heavy metal contamination globally.

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