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Advancements in Air Quality Monitoring for Atmospheric Lead (Pb) Detection Using Wireless Sensor Networks: A Comprehensive Review

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Abstract

Air quality monitoring is essential for safeguarding public health and environmental sustainability, particularly concerning lead (Pb) contamination, which poses significant risks to human well-being. This comprehensive review delves into advancements in air quality monitoring for atmospheric lead detection, focusing on the utilization of wireless sensor networks (WSNs). The review traces the evolution of monitoring techniques from traditional methods to advanced technologies, highlighting the transformative role of WSNs in environmental monitoring. WSNs offer advantages such as real-time data acquisition and spatial coverage, enabling continuous and widespread monitoring of lead concentrations in the atmosphere. Technological enhancements in WSNs for lead detection, including sensor technologies and integration with IoT and big data analytics, are examined. The review underscores the importance of sensor accuracy, calibration, and environmental impacts, alongside economic and regulatory challenges in deploying WSN-based monitoring systems. Furthermore, case studies demonstrate the successful deployment of WSNs for lead monitoring, showcasing their effectiveness in local and regional air quality management. Comparative analyses with traditional methods underscore the advantages of WSNs in terms of accuracy, reliability, and scalability. The framework outlines the approach for conducting a literature review, data collection, case study selection, interviews, comparative analysis, synthesis, and future directions. Recommendations for future research emphasize the need for advancements in sensor technology and network systems, aiming to address gaps and improve the efficacy of air quality monitoring initiatives. The implications of WSN-based lead monitoring for stakeholders, particularly in African countries like Nigeria, are discussed, highlighting the potential to address air quality challenges and promote sustainable development.

Keywords: Air quality monitoring, lead detection, Internet of Things, environmental sustainability, Nigeria.

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INTRODUCTION

Air quality serves as a fundamental determinant of public health, and its deterioration poses significant risks to human well-being and environmental sustainability alike (Kaur and Pandey 2021). The World Health Organization (WHO) has underscored air pollution as a paramount environmental threat to health, attributing millions of premature deaths annually to both outdoor and indoor air pollution (World Health Organization 2010; Akomolafe et al., 2024). The adverse effects of air pollution encompass a broad spectrum of health issues, ranging from respiratory diseases and cardiovascular ailments to cancer and adverse birth outcomes (Låg et al., 2020; Johnson et al., 2021). Notably, air pollution exacerbates existing health disparities, disproportionately impacting vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions (Fiter et al., 2023; Onaiwu and Elusoji, 2023; Onaiwu and Eferavware, 2023). Among the myriad pollutants, lead (Pb) contamination emerges as a particularly concerning issue due to its well-documented toxicity and persistence in the environment (Gautam et al., 2023; Idehen and Onaiwu, 2024). Lead is a neurotoxin capable of inflicting irreversible damage to the developing brains of children, manifesting in cognitive impairments, learning disabilities, and behavioural problems (Sachdeva et al., 2018). Even at low levels of exposure, lead has been associated with a myriad of health problems, including cardiovascular diseases, renal dysfunction, and reproductive disorders (Anyanwu et al., 2020). Sources of lead contamination encompass industrial processes, leaded gasoline, lead-based paints, and historical emissions that have accumulated in soil and sediments over time (Kumar et al., 2020; De-almeida et al., 2024). Over the years, air quality monitoring has undergone significant evolution driven by technological advancements and heightened awareness regarding the detrimental effects of air pollution on human health and the environment (Sokhi et al., 2021). This study delves into the transition from traditional monitoring methods to advanced technologies, with a specific focus on the transformative role of wireless sensor networks (WSNs) in revolutionizing air quality monitoring (Sokhi et al., 2021).

Historically, air quality monitoring heavily relied on manual sampling and analysis methods involving the collection of air samples at specific locations and subsequent analysis in laboratories through chemical analysis techniques (Zhang 2024). While these methods yielded valuable insights into air pollution levels, their scope and scalability were limited, often furnishing only localized and sporadic data (Parkinson et al., 2019). Moreover, the time lag between sample collection and analysis impeded real-time decision-making and response to air quality events. Additionally, traditional monitoring methods encountered challenges such as limited spatial coverage, high costs, and reliance on infrastructure. The advent of advanced monitoring technologies, including remote sensing, satellite imagery, and ground-based monitoring stations, marked a significant departure towards more comprehensive and integrated monitoring approaches (Brook et al., 2019). Remote sensing techniques, such as satellite-based monitoring systems, facilitated continuous monitoring of large geographical areas, furnishing spatially distributed data. Ground-based monitoring stations, equipped with sophisticated instrumentation and automated data collection systems, offered high-resolution data at specific locations, complementing satellite observations and providing valuable insights into local air quality conditions (Kumar et al., 2021). However, even with these advancements, challenges persisted, including limited spatial coverage, high costs, and infrastructure dependence.

The emergence of wireless sensor networks (WSNs) ushered in a new era in air quality monitoring by addressing these challenges and offering a scalable, cost-effective, and real-time monitoring solution. WSNs comprise spatially distributed autonomous sensors tasked with collecting, processing, and wirelessly transmitting data to a central server for analysis and interpretation (Fahmy 2016; Okafor 2023). These sensors boast various air quality monitoring capabilities, including the detection of pollutants such as particulate matter, volatile organic compounds, nitrogen oxides, and lead (Fahmy 2016). By deploying WSNs, researchers and environmental agencies can attain unprecedented spatial coverage, enabling continuous monitoring of air quality across large geographical areas in real-time (Fascista 2022).

Furthermore, WSNs offer several advantages over traditional monitoring methods. Firstly, they provide continuous, real-time data on air quality parameters, enabling prompt detection and response to air quality events and emergencies. Secondly, WSNs can be easily scaled up or down to accommodate different monitoring needs and objectives, rendering them suitable for both urban and rural environments. Thirdly, WSNs offer a cost-effective alternative to traditional monitoring methods, curtailing infrastructure costs and operational expenses associated with manual sampling and analysis. Lastly, WSNs facilitate the integration of data from multiple sensors and sources, enabling comprehensive analysis and interpretation of air quality data for decision-making and policy formulation (Othman and Shazali 2012).

Consequently, this review aims to address the pressing need for advancements in air quality monitoring, particularly within the realms of environmental science, environmental chemistry, and electrical/electronics engineering in Africa, with a special focus on Nigeria, Africa's largest economy both in GDP and population. Recommendations for future research emphasize the need for advancements in sensor technology and network systems, aiming to address gaps and improve the efficacy of air quality monitoring initiatives, thus contributing to sustainable development efforts in the region.

The review involved a systematic and comprehensive search of scholarly articles, research papers, and technical reports related to air quality monitoring, lead detection technologies, and wireless sensor networks (WSNs). Clear inclusion criteria were established, including publication dates from the past 10 years, articles written in English, and relevance to the research objectives.

The search strategy was transparently documented, detailing the search terms, databases searched (including PubMed, IEEE Xplore, and Google Scholar), and search date range (January 2012 to December 2022). The search terms included variations of "air quality monitoring," "lead detection technologies," and "wireless sensor networks," combined using Boolean operators.

Following the initial search, duplicates were removed, and the remaining literature was screened based on the inclusion criteria. Quality assessment was conducted using established tools such as the Critical Appraisal Skills Programme (CASP) checklist for qualitative research and the Joanna Briggs Institute (JBI) Critical Appraisal Tools for quantitative research. Studies deemed relevant and of sufficient quality were included in the review.

Thematic analysis was employed to identify key advancements, challenges, and trends in the field of air quality monitoring, with a particular focus on the application of WSNs for lead detection. Themes were identified through an iterative process of data coding and categorization. This analysis involved synthesizing information from diverse sources to develop a comprehensive understanding of the current state of research, including emerging technologies, innovative methodologies, and areas requiring further investigation.

OVERVIEW OF WIRELESS SENSOR NETWORKS (WSNS) FOR LEAD MONITORING:

Wireless Sensor Networks (WSNs) represent a groundbreaking advancement in environmental monitoring, facilitating a distributed and interconnected system of sensors dedicated to real-time data collection and transmission (Liang, 2020). Designed specifically for monitoring lead (Pb), WSNs rely on core components—sensors, nodes, and gateways—that are crucial for ensuring the network's effective operation (Kocakulak and Butun, 2017).

Components and Functionality of WSNs:

Sensors: At the heart of WSNs lie sensors, miniature electronic devices equipped with sensing elements proficient in detecting various environmental parameters. In the context of lead monitoring, these sensors encompass technologies for detecting lead concentrations, ensuring precise and continuous monitoring of lead levels in the environment as shown in Figures 1 and 2. Additionally, sensors may integrate functionalities for measuring complementary parameters such as temperature and humidity, providing comprehensive environmental data (Awolusi et al., 2018).

Nodes: Nodes, often referred to as motes, serve as the core communication and processing units within the wireless sensor network. Each node comprises essential components including a microcontroller, memory, transceiver, and power source (Sara and Sridharan 2014). In lead monitoring applications, nodes are responsible for collecting data from the sensors, performing local processing to filter or aggregate the data, and wirelessly transmitting it to neighbouring nodes or the gateway for further analysis as shown in Figure 2 (Abdulkarem et al., 2020).

Gateways: Gateways serve as the vital link between the wireless sensor network and external systems or networks as shown in Figures 1 and 2. Tasked with receiving data transmitted by the sensor nodes, gateways aggregate this data before forwarding it to a central server or cloud-based platform for storage and analysis. Moreover, gateways facilitate connectivity to external devices or networks, enabling remote monitoring and control of the sensor network, thereby enhancing the effectiveness and accessibility of lead monitoring efforts (Abdulkarem et al., 2020).

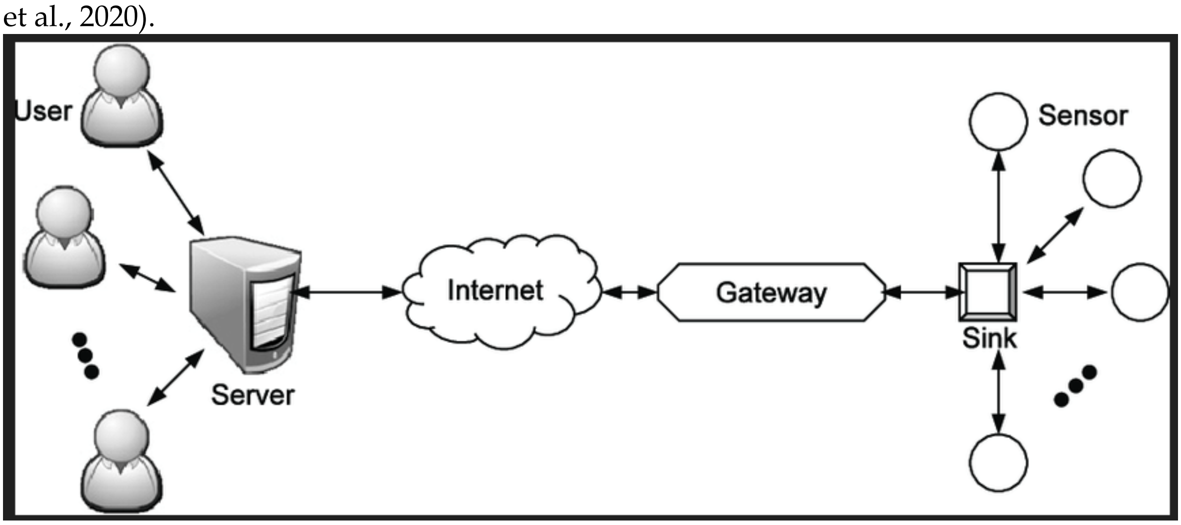

Figure 1: Architecture of a Wireless Sensor Network for Lead Monitoring (Mendes, and Rodrigues 2011).

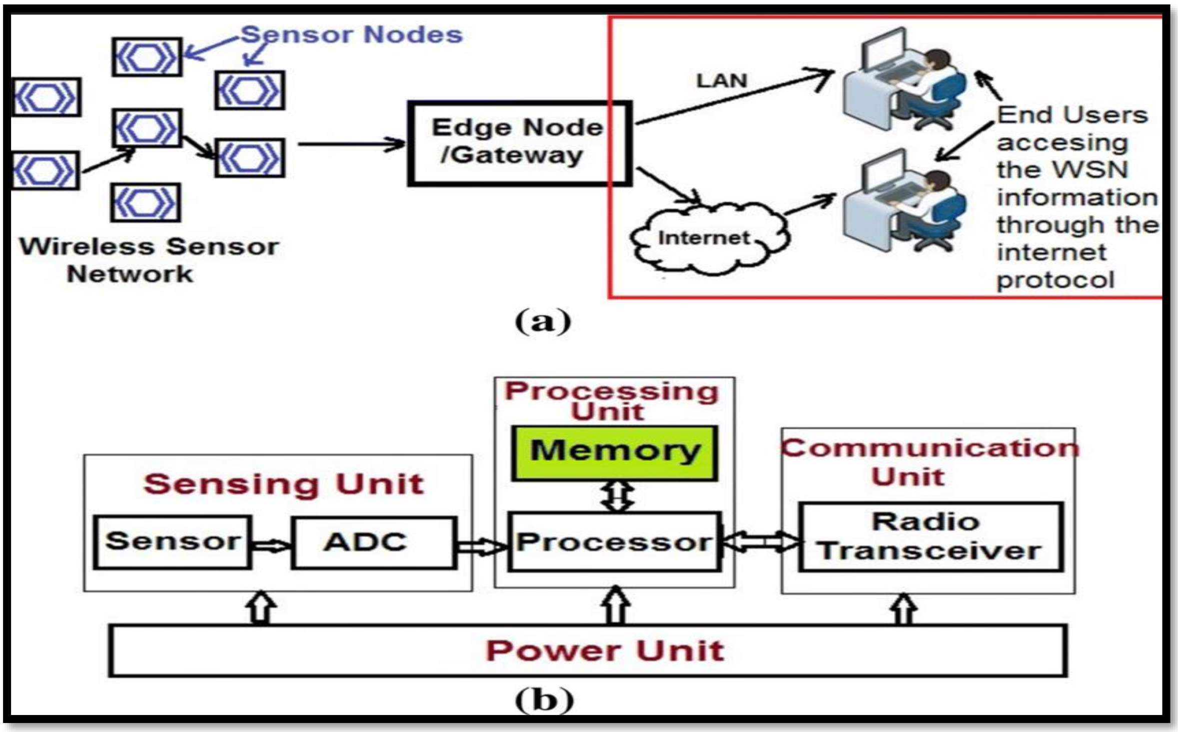

Figure 2: Data Flow in a Wireless Sensor Network for Lead Monitoring (Sharma et al., 2019)

Benefits of Using WSNs in Lead Environmental Monitoring:

Real-time Data Acquisition: WSNs offer the invaluable capability of providing real-time data on lead concentrations in the environment, enabling prompt detection of changes or anomalies. This real-time monitoring allows stakeholders to quickly address potential contamination incidents and reduce risks to human health and the environment.

Scalability: An inherent advantage of WSNs is their scalability, facilitating seamless expansion or contraction to meet varying monitoring needs. Additional sensor nodes can be deployed to enhance spatial coverage or data resolution, while existing nodes can be repositioned or redeployed to adapt to evolving environmental conditions, ensuring comprehensive and adaptive lead monitoring strategies. Advancements in sensor technology and network systems can further support scalability efforts.

Cost-effectiveness: WSNs present a cost-effective alternative to traditional lead monitoring methods, which often involve labor-intensive manual sampling and laboratory analysis. Once deployed, WSNs require minimal ongoing maintenance and can operate autonomously for extended periods, reducing the need for frequent human intervention and minimizing operational expenses associated with lead monitoring initiatives.

Flexibility: WSNs offer unparalleled flexibility in deployment, capable of operating in diverse environmental settings, including remote or inaccessible areas where traditional monitoring methods may be impractical or costly. Leveraging wireless communication technologies, WSNs effectively overcome geographical barriers, providing valuable insights into lead concentrations across expansive regions, thereby facilitating comprehensive lead monitoring efforts.

TECHNOLOGICAL ENHANCEMENTS IN WSNS FOR LEAD DETECTION

Sensor Technologies for Lead Detection:

Lead detection in the atmosphere requires sensors capable of accurately and selectively measuring trace levels of lead particles or vapours. Several types of sensors have been developed and employed for this purpose, each with its own set of advantages and limitations.

Electrochemical Sensors:

Electrochemical sensors are pivotal in lead detection due to their remarkable sensitivity and selectivity, capitalizing on the electrochemical reaction between lead ions and electrode surfaces. This interaction generates a measurable electrical signal, directly proportional to the concentration of lead in the air (Awolusi et al., 2018).

Recent strides in electrochemical sensor technology have honed in on enhancing sensitivity, response time, and stability, culminating in more precise and dependable lead detection in diverse environmental settings (Zheng et al., 2024). These advancements mark pivotal milestones in the evolutionary trajectory of electrochemical sensor technology, each underpinning a distinct facet of progress.

The genesis of Screen-Printed Electrodes (SPEs) stands as a watershed moment in electrochemical sensor fabrication. Spearheading a simple, cost-effective, and scalable manufacturing process, SPEs heralded the mass production of disposable electrochemical sensors, revolutionizing their utility across various applications (Sivaranjanee et al., 2022). Subsequently, the discovery and synthesis of nanostructured materials like carbon nanotubes (CNTs) and graphene unfurled novel prospects in electrode material development. These materials, with their unique properties, including heightened sensitivity, conductivity, and catalytic activity, ushered in a new era of electrochemical sensing prowess (Rosaiah et al., 2024).

Moreover, the drive toward miniaturization propelled the development of compact, portable, and wearable electrochemical sensors. Using microfabrication techniques like photolithography and microfluidics has allowed for the precise design and integration of sensor components on tiny platforms. This advancement has transformed the use and adaptability of electrochemical sensors in various fields (Mohan et al., 2022). Advancements in signal processing algorithms stand as a cornerstone in refining the accuracy, reliability, and speed of electrochemical sensor measurements. Techniques such as impedance spectroscopy and cyclic voltammetry furnish invaluable insights into electrochemical behaviour, amplifying data analysis capabilities and the interpretation of sensor output (Bhatia et al., 2024).

Lastly, the integration of electrochemical sensors with wireless communication technologies has enabled remote monitoring and real-time data transmission. Leveraging wireless sensor networks (WSNs), distributed sensor arrays have been seamlessly deployed, bolstering environmental monitoring capabilities, including air quality assessment and pollution detection (Liang et al., 2023). The flowchart illustrating the evolution of electrochemical sensor technology is explicitly explained in Figure 3.

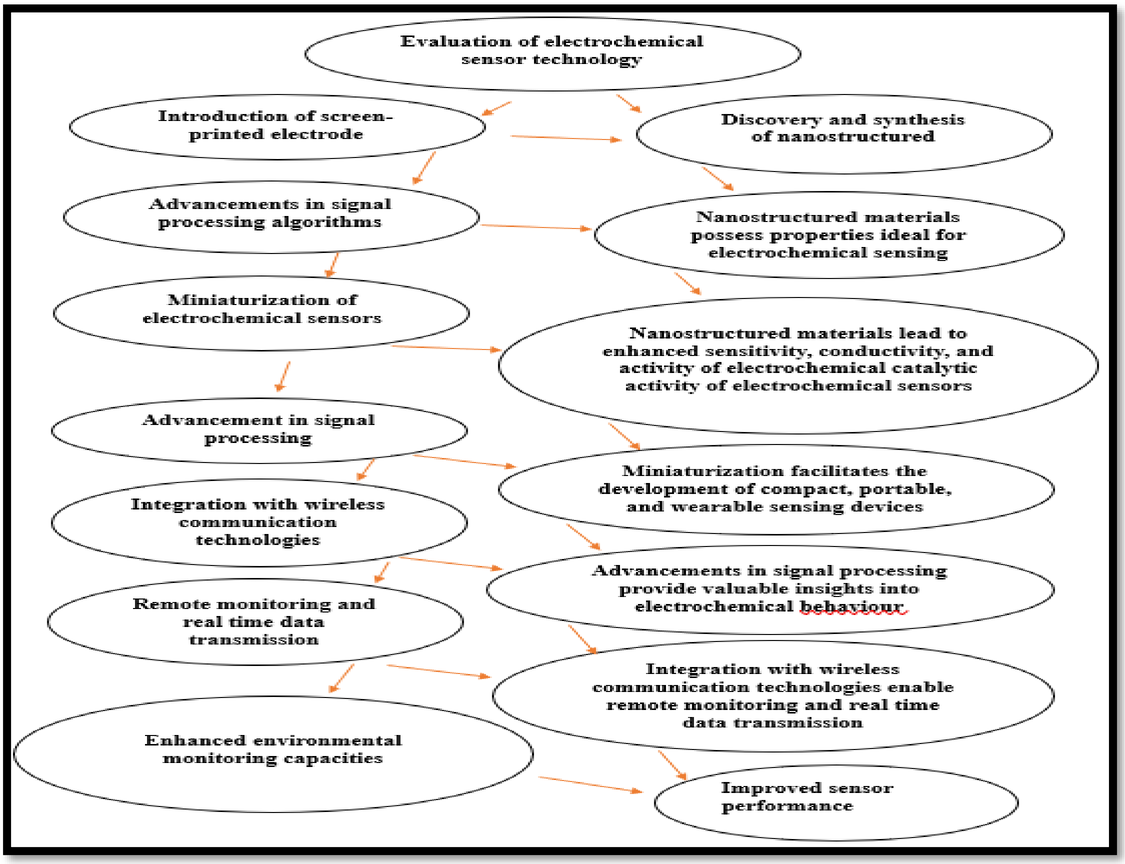

Figure 3: Flowchart illustrating the evolution of electrochemical sensor technology (Mei and Ahmad 2021).

Optical Sensors: Optical sensors offer another approach to lead detection, leveraging principles of light absorption or scattering to detect lead particles or vapours in the atmosphere. These sensors typically use laser-induced fluorescence, light absorption spectroscopy, or light scattering techniques to detect and quantify lead concentrations (Fonollosa et al., 2018). While optical sensors can provide rapid and real-time measurements, they may be less sensitive than electrochemical sensors and susceptible to interference from other substances present in the air. Figure 4, provides a schematic visualisation of sensor development and heavy metal ions detection as reported by Kulpa-Koterwa et al., (2021) while Figure 5 gives credence to wireless optical sensor operations (Kassal et al., 2018).

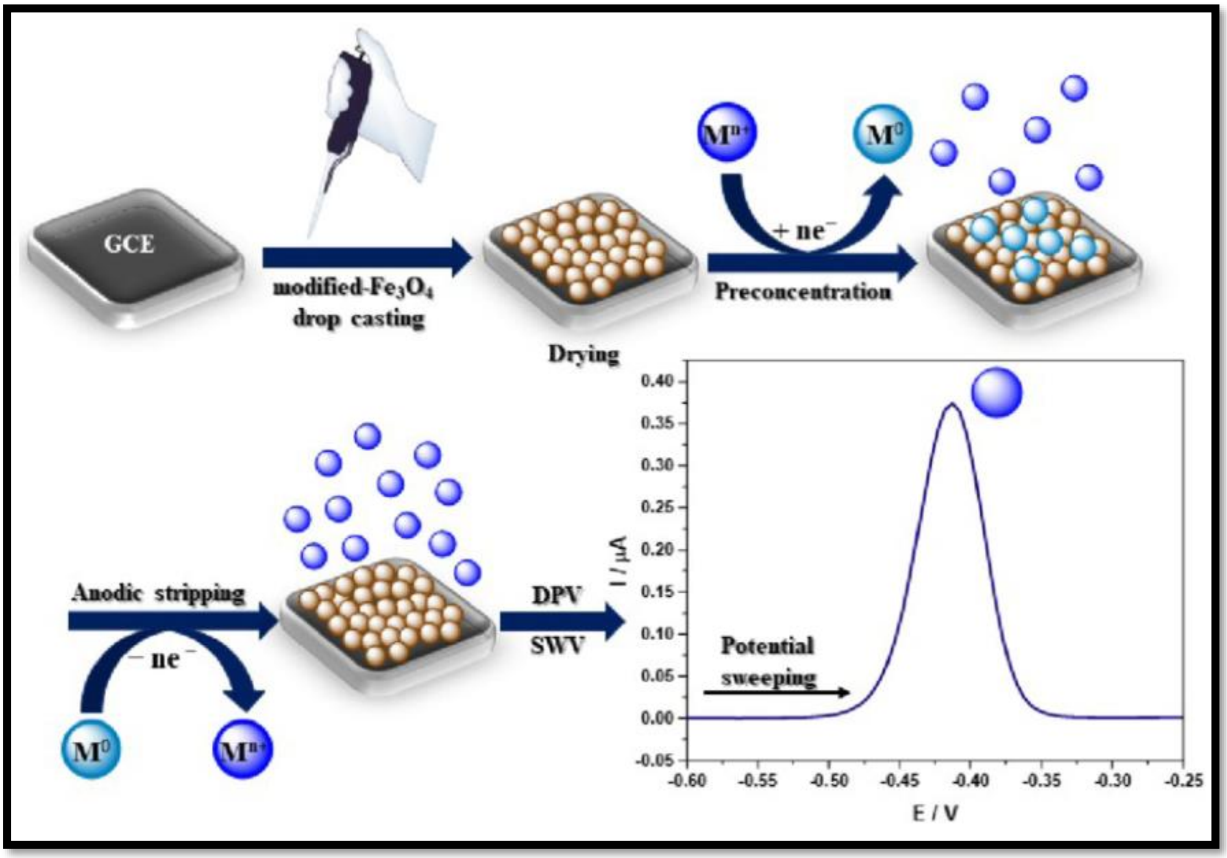

Figure 4: Schematic visualisation of sensor development and heavy metal ions detection (Kulpa-Koterwa et al., (2021)

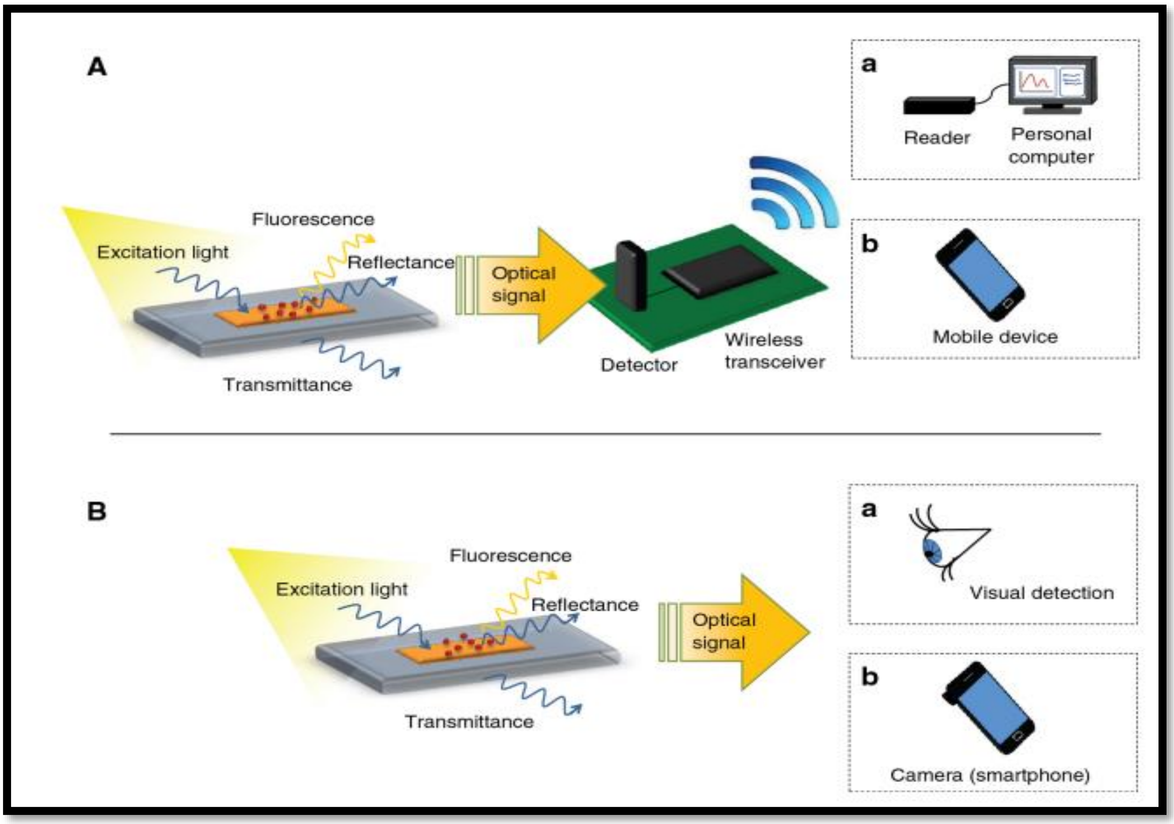

Figure 5: (A) Wireless optical sensor operation schematic. (B) Mobile optical sensors allow wireless readout via the naked eye or a remote camera, without radio communication (Kassal et al., 2018).

Semiconductor Gas Sensors for Lead Detection

Semiconductor gas sensors are increasingly utilized for detecting lead, capitalizing on the changes in electrical conductivity of semiconductor materials in response to lead ions. These sensors are noted for their low cost, potential for miniaturization, and minimal power demands, which make them ideal for integration into wireless sensor networks (Baraneedharan et al., 2023). Despite these advantages, semiconductor gas sensors face challenges in sensitivity and selectivity, which are critical for effective lead detection, particularly in trace amounts. The reduced sensitivity and selectivity can be attributed to the inherent material properties of semiconductors used in these sensors (Nikolic et al., 2020). In environments with complex matrices such as industrial zones or areas with high vehicular emissions, the presence of other volatile organic compounds and varying temperatures can significantly affect the sensor's performance by interfering with the detection of lead ions (Azzouz et al., 2019). This limitation restricts their use in applications requiring precise quantification of lead in diverse environmental settings. Comparatively, while semiconductor gas sensors are advantageous for their durability and operational efficiency, they may not perform as well as electrochemical or optical sensors in scenarios requiring ultra-sensitive detection capabilities. Electrochemical sensors, for example, provide higher sensitivity in detecting low levels of lead due to their direct electrochemical reaction mechanism. In contrast, optical sensors offer rapid detection times, which can be crucial in real-time monitoring situations. Ongoing research is focused on enhancing the performance of semiconductor gas sensors through material engineering and advanced circuitry design. Innovations such as incorporating nanostructured materials or employing hybrid sensor systems are being explored to overcome the limitations in sensitivity and selectivity (Nikolic et al., 2020).

Table 1 illustrates this by comparing the sensitivity and selectivity of semiconductor gas sensors against other types of sensors across various environmental conditions. It provides a clear and concise comparison, emphasizing the specific applications where semiconductor gas sensors are most effective and where alternative sensor technologies might be preferred.

Table 1: Comparison of Sensor Types by Sensitivity and Selectivity in Different Environmental Conditions

Sensor Type	Environmental Condition	Sensitivity	Selectivity	Preferred Applications	Reference
Semiconductor Gas Sensors	Industrial Zones	Low	Medium	Cost-effective monitoring	Zhang et al., 2020
	High Vehicle Emissions	Low	Low	General air quality tracking	Zhang et al., 2020
Electrochemical Sensors	Trace Contaminants	High	High	Precise quantification of lead	Mohan et al., 2022
	Diverse Matrices	High	High	Sensitive environments	Bhatia et al., 2024
Optical Sensors	Real-time Monitoring	Medium	Medium	Rapid detection and assessment	Kassal et al., 2018

The understanding of these dynamics will enhance future developments in semiconductor gas sensor technology and may well bridge the current gaps in performance, broadening their applicability in environmental monitoring and industrial safety applications.

Ion-Selective Electrodes (ISEs) for Lead Detection

Ion-selective electrodes (ISEs) represent a sophisticated approach for detecting lead ions, showcasing exceptional selectivity and sensitivity. These electrodes operate through a specialized membrane, typically made from polymeric materials embedded with specific ionophores that selectively bind to lead ions (Mustafa et al., 2024)). This interaction generates a measurable electrical potential directly proportional to the concentration of lead, whether in the solution or the gas phase (Shao et al.,2020). Recent advancements in ISE technology have extended their application beyond traditional aqueous environments into gas-phase monitoring. Innovations such as the development of vapor-sensitive membranes have enabled the use of ISEs in broader environmental contexts, providing a valuable tool for continuous monitoring of air quality (Janata 2022). These enhancements not only increase the versatility of ISEs but also open up new frontiers for real-time environmental surveillance. Comparatively, ISEs offer distinct advantages over other lead detection methods such as electrochemical sensors and semiconductor gas sensors, particularly in terms of selectivity. The specific interaction between the membrane and lead ions minimizes interference from other substances, making ISEs highly effective in complex matrices where competing ions may be present (Janata 2022). This high fidelity in detection is crucial for applications requiring precise quantification of lead levels in both industrial and environmental settings. ISEs are particularly advantageous in scenarios requiring rapid yet accurate assessments of lead contamination in situ. For instance, in water treatment facilities or sites exposed to industrial emissions, ISEs can provide immediate data crucial for compliance with environmental safety standards. Additionally, the potential expansion into gas-phase applications suggests that ISEs could soon be deployed in atmospheric monitoring, offering tools for urban air quality assessments where lead and other heavy metals are concerns.

However, the use of ISEs is not without challenges. The electrodes require regular calibration to maintain accuracy, and their selectivity can be compromised by the presence of other high-affinity ions in certain environments (Sharma et al., 2021). Addressing these limitations involves ongoing research into membrane technology and electrode design, aiming to enhance the robustness and operational lifespan of these sensors. **Table 2** highlights the innovative features and practical applications of Ion-Selective Electrodes (ISEs) for lead detection. With advancements extending their use from aqueous to gas-phase environments, ISEs offer precise, selective, and sensitive monitoring solutions crucial for environmental and industrial settings. This overview is supported by recent research and developments in the field (Wasilewski et al., 2019; Yew et al., 2019; Mishra et al., 2023; Sharma, et al., 2023; Lapizco-Encinas and Zhang 2023).

Table 2: Features and Applications of Ion-Selective Electrodes (ISEs) for Lead Detection

Feature	Description	Application Example	Reference
Selectivity	High selectivity due to membrane that specifically interacts with lead ions.	Used in mining operations to monitor lead levels.	(Awual 2019).
Sensitivity	Capable of detecting very low concentrations of lead, with measurements directly proportional to lead concentration.	Monitoring trace levels of lead in drinking water.	(Ekrami et al., 2021)
Operational Environment	Traditionally used in aqueous solutions but now applicable in gas-phase through vapor-sensitive membranes.	Air quality monitoring in urban and industrial areas.	(Janata 2022)
Interference Resistance	Minimal interference from other substances due to the specificity of the membrane ionophores.	Complex industrial environments with mixed emissions.	(Zhuang et al., 2023).

Feature	Description	Application Example	Reference
Technological Advancements	Development of vapor-sensitive membranes for gas-phase detection.	Real-time air monitoring for environmental compliance.	(Janata 2022)
Limitations	Requires calibration and may be affected by high-affinity competing ions.	Regular maintenance is needed in fluctuating environments.	(Zhuang et al., 2023)

Discussion of Advances in Sensor Technology Improving Sensitivity and Selectivity

Recent advancements in sensor technology have focused on improving the sensitivity, selectivity, and reliability of lead detection sensors, addressing key challenges such as interference from other substances, low detection limits, and environmental robustness.

Nanomaterial-Based Sensors

One of the most promising developments in sensor technology involves the use of nanomaterials, including carbon nanotubes, graphene, and metal oxides. These materials offer unique properties such as high surface area and enhanced catalytic activity, which significantly improve the sensitivity and selectivity of sensors towards lead ions (Li et al., 2022). For instance, the functionalization of carbon nanotubes with specific receptors enhances their ability to target and bind lead ions selectively, minimising interference from other substances found in environmental samples. This method's efficacy was notably demonstrated in a study conducted in industrial zones where these sensors effectively differentiated lead ions from other toxic metals, showcasing not only technological prowess but also practical utility (Li et al., 2022).

Selective Coatings and Molecular Recognition Elements

Advancements in selective coatings and molecular recognition technologies have also marked significant strides in sensor technology. These coatings are engineered to possess a high affinity for lead ions, which enhances the selectivity of sensors while reducing unwanted cross-reactivity with other chemical species in the environment. This technology has been applied in sensors deployed in water treatment facilities, where their ability to withstand complex mixtures and maintain accuracy over prolonged periods has been crucial (DuChanois et al., 2021; Li et al., 2022). Moreover, the development of durable coatings contributes to the sensors' longevity and stability, ensuring reliable performance under varying environmental conditions (Demchenko 2023).

Integration with Signal Processing and Machine Learning

The integration of advanced signal processing and machine learning techniques has revolutionised the functionality of lead detection sensors by enabling precise real-time data analysis and interpretation (Krokidis et al., 2022). Algorithms specialized in feature extraction and pattern recognition enhance the sensors' ability to distinguish lead ions in noisy environments, effectively increasing their sensitivity and selectivity. Furthermore, machine learning algorithms can dynamically adapt sensor operations to fluctuating environmental conditions, optimizing performance without manual recalibration (Qiu et al., 2022). A notable application of this technology has been in urban air quality monitoring, where sensors equipped with these algorithms have accurately tracked pollution levels, providing data essential for environmental health assessments (Qiu et al., 2022; Krokidis et al., 2022).

Cross-references and Sustainability Considerations

These technological advancements are part of a broader trend towards sustainable and environmentally friendly sensor technologies, as discussed in sections 3.2.1 and 3.2.2. Moreover, the environmental impact of manufacturing and disposing of these advanced materials is a crucial aspect of their development. Efforts are continuously made to mitigate these impacts, ensuring that the new sensor technologies adhere to principles of sustainability and environmental stewardship.

Table 3, provides a structured overview of each technological advancement discussed in Section 3.2, highlighting the functionalities, practical implications, and academic references to support their applications. The layout was designed to be engaging by offering direct insight into how each technology enhances the capabilities of lead detection sensors. Thus, emphasizing the real-world relevance and scientific backing of the developments.

Table 3: Overview of Technological Advancements in Lead Detection Sensor Technology

Section	Technology	Key Features	Practical Applications	Notable Contributions	References
3.2.1	Nanomaterial Based Sensors	High surface area, enhanced catalytic activity and functionalized to target lead ions	Industrial monitoring and Environmental testing	Effective differentiation of lead in complex matrices	(Li et al., 2022)
3.2.2	Selective Coatings and Molecular Elements	High affinity for lead ions, reduces cross-reactivity and durable coatings	Water treatment facilities and Industrial use	Maintained accuracy in complex mixtures over time	(DuChanois et al., 2021; Li et al., 2022)
3.2.3	Signal Processing and Machine Learning	Real-time data analysis, feature extraction and pattern recognition and Adaptive algorithms	Urban air quality monitoring and Industrial use	Enhanced sensitivity and selectivity in noisy settings	(Qiu et al., 2022; Krokidis et al., 2022)

Integration of Wireless Sensor Networks (WSNs) with Other Technologies

Recent advancements in sensor technology have spurred the integration of wireless sensor networks (WSNs) with other cutting-edge technologies, such as the Internet of Things (IoT) and big data analytics, to significantly enhance the capabilities and effectiveness of environmental monitoring systems (Mowla et al., 2023)., Particularly in the context of lead detection.

Analysis of the Role of IoT and Big Data Analytics in Enhancing WSN Capabilities

The Internet of Things (IoT) is a network comprising interconnected devices and sensors that collect, transmit, and exchange data over the Internet (Mouha 2021). Merging WSNs with IoT platforms, and environmental monitoring systems can harness the power of connectivity and real-time data exchange to bolster monitoring capabilities and facilitate more informed decision-making (Rani and Taneja 2024).

Data Integration and Interoperability

IoT platforms offer a unified framework for seamlessly integrating data from diverse sources, including WSNs, remote sensing systems, and external databases (Mouha 2021; Rani and Taneja 2024). Through data aggregation and harmonisation, environmental monitoring systems can attain a comprehensive understanding of air quality dynamics and trends, thereby enabling more precise and reliable assessments of lead contamination levels.

Real-time Monitoring and Alerting

IoT-enabled WSNs facilitate prompt data acquisition and transmission in real-time, enabling swift detection of lead contamination events and timely dissemination of alerts to pertinent stakeholders (Kumar et al., 2023). Strategic deployment of sensor nodes coupled with IoT connectivity empowers environmental agencies to establish robust early warning systems for lead pollution, facilitating proactive measures to mitigate risks and safeguard public health (Nizeyimana et al., 2023).

Scalability and Flexibility

IoT platforms provide scalable and adaptable solutions for deploying and managing WSNs across vast geographical areas (Nizeyimana et al., 2023). Leveraging cloud-based infrastructure and edge computing technologies, environmental monitoring systems can dynamically allocate resources and adjust to evolving monitoring needs and objectives (Kumar et al., 2023). This scalability and flexibility are particularly invaluable for monitoring lead contamination in diverse environmental settings, ranging from urban industrial zones to remote rural regions.

Data Fusion and Correlation

Big data analytics techniques, such as data fusion and correlation, empower environmental monitoring systems to amalgamate data from multiple sources and sensors, including WSNs, satellite imagery, and ground-based monitoring stations (Fascista 2022). By correlating environmental parameters with lead contamination levels, big data analytics unveil spatial and temporal patterns, hotspots, and potential sources of lead pollution, thereby facilitating targeted interventions and remediation efforts.

Predictive Modeling and Risk Assessment

Big data analytics enable environmental agencies to develop predictive models and risk assessment tools for lead contamination by harnessing historical data, environmental parameters, and machine learning algorithms. Forecasting lead pollution levels and evaluating associated risks empowers decision-makers to implement proactive measures aimed at preventing and mitigating lead exposure, thereby safeguarding public health and environmental quality (Fascista 2022).

EMPIRICAL EVALUATION ON LEAD (PB) MONITORING WITH WSNs

Monitoring Techniques for Lead (Pb), Case Studies and Findings

WSN-based monitoring systems offer an effective means to detect and monitor lead levels in ambient air. When equipped with lead-specific sensors, they are deployed in target areas to measure lead concentrations. These sensors utilize various detection principles, such as electrochemical sensing, to accurately measure lead levels in real-time. Communication protocols like Zigbee or GSM are used to transmit data from sensor nodes to a central server for analysis and visualization. Wang et al. developed a wireless sensor network for outdoor air pollution monitoring, including lead concentrations, using GPRS communication for data transmission. Their system demonstrated the feasibility of real-time lead monitoring and data dissemination to the public (Wang et al., 2013).

Mansour et al. (2014) presented an outdoor air quality monitoring system based on WSNs, capable of sensing lead (Pb) concentrations among other pollutants. Their system utilized Zigbee communication for data transmission and employed clustering protocols to improve network efficiency.

Sherin et al. (2014) proposed a low-cost wireless sensor network-based indoor air quality monitoring system that included lead (Pb) sensors. Their system showcased the ability to measure lead concentrations accurately and compared favourably with commercially available monitoring systems.

Movva et al. (2016) demonstrated real-time pollution monitoring using WSNs, including lead (Pb) levels, in industrial areas. Their system utilized sensor motes calibrated for lead detection and employed multi-hop data aggregation for efficient data transmission.

In 2017, a significant study by Sun et al introduced a novel electrochemical sensor for WSNs specifically designed to detect low concentrations of lead in industrial settings. This study underscored the importance of enhancing sensor sensitivity to detect minute lead concentrations, which are often overlooked but critical for early warning systems (Sun et al., 2017).

A year later, Lakhiar and colleagues implemented a WSN in a densely populated urban area to monitor air quality, including lead levels. Their system utilized cloud-based data analytics to provide real-time monitoring and predictive analysis of lead pollution patterns. This approach demonstrated the utility of cloud integration in environmental monitoring (Lakhiar et al., 2018).

In 2020, a breakthrough was reported by Priyadarshi et al. who developed a low-cost WSN using graphene-based sensors for lead detection. Their study highlighted the cost-effectiveness of the sensors, which made it feasible to deploy extensive networks covering larger geographic areas without compromising performance (Priyadarshi et al., 2020).

During 2020, researchers Abid et al focused on improving the energy efficiency of WSNs for sustainable long-term monitoring. Their work resulted in a solar-powered WSN system that was particularly effective in remote areas, reducing the operational costs and maintenance frequency of lead monitoring networks (Abid et al., 2020).

In 2021, Gilik et al introduced an advanced machine-learning model that was incorporated into WSNs to predict lead pollution levels based on historical and real-time data. This model helped in understanding the dynamic patterns of lead distribution and was crucial for developing more effective environmental policies (Gilik et al., 2021)

A significant advancement came in 2022 when Uka et al. developed a multi-sensor WSN that not only monitored lead but also other heavy metals simultaneously. This integrated approach provided a comprehensive view of air quality and pollutant interactions, which is critical for comprehensive environmental health assessments (Uka et al., 2022)

By 2023, advancements in data transmission were highlighted in the work of Saleem et al. who utilized 5G technology to enhance the reliability and speed of data communication within WSNs. This improvement was particularly crucial in urban environments, where previous technologies faced significant interference (Saleem et al., 2023)

Looking ahead to 2024, Lu et al. projected that further integration of artificial intelligence and IoT in WSNs will make real-time monitoring more efficient and precise. Upcoming research is expected to focus on autonomous sensor networks that can self-diagnose and repair, minimizing downtime and maintenance costs (Lu et al., 2024).

The summary of the **c**omparative Analysis of Lead Monitoring Techniques in Air Quality Sensor Networks as reported by each researcher is shown in Table 4.

Table 4. Comparative Analysis of Lead Monitoring Techniques in Air Quality Sensor Networks

Monitoring Technique	Deployment Details	Case Study Description	Key Findings	Reference
Wireless sensor network with lead-specific sensors. Data transmission through GPRS.	Solar-powered stationary sensor nodes deployed.	Real-time outdoor air pollution monitoring system. Including lead concentrations.	Feasibility of real-time lead monitoring demonstrated. Data dissemination to the public was achieved.	Wang et al., 2013
Wireless sensor network with Zigbee communication. Clustering protocols for efficiency.	Sensor nodes mounted on Libelium's Wasp mote.	Outdoor air quality monitoring system. Including lead (Pb) concentrations.	Efficient lead monitoring was demonstrated. Zigbee communication is used for data transmission. Clustering protocols improved network efficiency.	Mansour et al. (2014)
Low-cost wireless sensor network-based indoor air quality monitoring system. Lead (Pb) sensors included.	Micro gas sensors integrated with Arduino board and XBee modules.	Indoor air quality monitoring system. Including lead (Pb) concentrations.	Low-cost system with lead monitoring capability demonstrated. System performance is compared favourably with commercial systems.	Sherin et al. (2014)
Real-time pollution monitoring using WSNs. Lead (Pb) levels measured. Data transmission through multi-hop aggregation.	Sensor motes calibrated for lead detection. Deployment in the industrial belt of Hyderabad city.	Real-time pollution monitoring system. Including lead (Pb) concentrations.	Real-time monitoring of lead concentrations achieved. Multihop data aggregation employed for efficient data transmission.	Movva et al. (2016)

Table 4. Comparative Analysis of Lead Monitoring Techniques in Air Quality Sensor Networks cond.,

Monitoring Technique	Deployment Details	Case Study Description	Key Findings	Reference
Electrochemical sensor for WSNs	Stationary sensor nodes deployed in industrial settings	Novel sensor designed to detect low concentrations of lead	Enhanced sensor sensitivity critical for early warning systems	Sun et al. (2017)
WSN with cloud-based data analytics	Urban deployment of sensor nodes	Real-time monitoring and predictive analysis of urban lead pollution	Demonstrated the utility of cloud integration in environmental monitoring	Lakhiar et al. (2018)
Low-cost WSN using graphene-based sensors	Extensive network deployment covering large geographic areas	Cost-effective monitoring of lead in diverse environments	Reduced costs enabled broader deployment without sacrificing performance	Priyadarshi et al., 2020
Solar-powered WSN for sustainable monitoring	Deployment in remote areas	Long-term monitoring with reduced operational costs	Solar power significantly reduced the energy and maintenance costs of WSNs	Abid et al. (2020)
WSN integrated with machine learning models	Varies, adapted to urban and industrial areas	Predictive modelling of lead pollution patterns based on historical and real-time data	Enhanced understanding and policy development through dynamic pattern recognition	Gilik et al. (2021)
Multi-sensor WSN monitoring lead	Deployment across multiple	Comprehensive air quality monitoring system	Provided a holistic view of air quality and pollutant interactions, enhancing	Uka et al. (2022)

and other heavy metals	environmental settings		environmental health assessments	
WSN utilizing 5G technology for data transmission	Urban environments	Enhanced data transmission in high-interference areas	Improved reliability and speed of data communication essential for urban WSN deployment	Saleem et al. (2023)
Autonomous WSN integrated with AI and IoT	Predicted deployment in diverse and remote locations	Autonomous monitoring networks capable of self-diagnosis and repair	Projected to minimize downtime and maintenance costs, increasing monitoring efficiency	Lu et al., 2024

Comparative Analysis with Traditional Methods:

Traditional methods of lead monitoring, such as manual sampling and laboratory analysis, have several limitations compared to WSN-based approaches. Manual sampling is often labour-intensive, time-consuming, and expensive, requiring trained personnel to collect samples and transport them to laboratories for analysis. Moreover, manual sampling provides only localized and sporadic data, limiting its ability to capture spatial and temporal variations in lead concentrations.

In contrast, WSNs offer several advantages over traditional methods, including continuous monitoring, which enables real-time tracking of lead concentrations, providing a more comprehensive and up-to-date picture of air quality conditions. WSNs can be deployed across large geographical areas, providing spatially distributed data on lead contamination levels and enabling the identification of hotspots and sources of pollution. Additionally, WSNs offer a cost-effective alternative to traditional monitoring methods, reducing the need for manual labor and infrastructure associated with manual sampling and analysis.

However, WSNs also have limitations. The accuracy and reliability of WSN-based sensors may vary depending on factors such as sensor calibration, environmental conditions, and sensor drift. Furthermore, WSNs rely on wireless communication for data transmission, which may be susceptible to interference or signal loss in urban or industrial environments. Overall, while WSNs offer significant advantages over traditional methods in terms of cost-effectiveness, spatial coverage, and real-time monitoring capabilities, careful consideration of sensor accuracy, data quality, and network reliability is essential to ensure the effectiveness of WSN-based lead monitoring systems.

Challenges and Limitations

Technical and Operational Challenges: this has to do with the **identification of issues related to sensor accuracy, calibration, and environmental impacts as discussed below.**

Sensor Accuracy: One of the primary challenges in air quality monitoring, including lead detection, is ensuring the accuracy and reliability of sensor measurements. Variations in sensor performance, drift, and cross-sensitivity to other environmental factors can introduce errors and uncertainties in the data collected by wireless sensor networks (WSNs). Ensuring sensor accuracy requires regular calibration, quality control procedures, and validation against reference methods or instruments.

Calibration: Calibrating sensors for lead detection presents unique challenges due to the lack of standardized calibration procedures and reference materials. Developing accurate calibration methods for lead sensors requires careful characterization of sensor response to lead concentrations across a range of environmental conditions and validation against certified reference materials. Additionally, factors such as sensor aging, fouling, and environmental interference can affect calibration stability and require periodic recalibration to maintain measurement accuracy.

Environmental Impacts: WSNs deployed for lead monitoring may be susceptible to environmental factors such as temperature variations, humidity, and exposure to contaminants, which can influence sensor performance and data quality. Ensuring the robustness and reliability of WSNs in harsh environmental conditions requires careful selection of sensor materials, housing designs, and deployment strategies to minimize environmental impacts and ensure data integrity.

Economic and Regulatory Challenges: This has to do with the **cost considerations for widespread deployment and compliance with standards and regulations as discussed below.**

Cost Considerations: The widespread deployment of wireless sensor networks (WSNs) for lead monitoring entails significant upfront and operational costs, including sensor procurement, installation, maintenance, and data management. While advancements in sensor technology and manufacturing processes have led to reductions in sensor costs, scalability remains a challenge for large-scale deployment. Additionally, ongoing operational expenses such as sensor recalibration, battery replacement, and data transmission may contribute to the total cost of ownership of WSN-based monitoring systems.

Compliance with Standards and Regulations: Environmental monitoring systems, including those deployed for lead detection, must comply with regulatory standards and requirements established by governmental agencies and international organizations. Ensuring compliance with air quality standards and regulations involves adhering to stringent measurement protocols, quality assurance procedures, and reporting requirements. Furthermore, regulatory compliance may necessitate additional investments in equipment, personnel training, and data validation to demonstrate the accuracy, reliability, and traceability of monitoring data.

Integration with Existing Infrastructure: Integrating WSN-based monitoring systems with existing infrastructure, such as air quality monitoring networks and data management platforms, presents challenges related to interoperability, data integration, and compatibility. Ensuring seamless data exchange and integration requires standardized protocols, data formats, and communication interfaces to facilitate interoperability and enable collaboration among stakeholders.

CONCLUSION

Wireless Sensor Networks (WSNs) have emerged as a revolutionary technology for lead detection in the atmosphere, offering real-time, spatially distributed monitoring capabilities that were previously unattainable with traditional methods. This review has highlighted the significant advancements in WSN-based lead monitoring, including improved sensor technologies, enhanced data processing techniques, and integrated IoT solutions. By leveraging the power of connectivity and data analytics, WSNs are transforming the landscape of air quality monitoring, enabling more accurate, timely, and cost-effective detection of lead pollution.

To further advance the field of WSN-based lead monitoring, future research efforts should focus on the development of advanced sensor technologies and network systems tailored to the specific needs and challenges of environmental monitoring in diverse settings, including urban, industrial, and rural areas. Emphasis should be placed on improving sensor accuracy, reliability, and robustness to environmental conditions, as well as enhancing data processing algorithms for real-time analysis and interpretation. Additionally, research initiatives should explore innovative approaches for integrating WSNs with emerging technologies such as artificial intelligence (AI) and blockchain to enhance data security, interoperability, and transparency.

The findings of this review have significant implications for policymakers, communities, and environmental scientists in Nigeria and other African countries. Embracing WSN-based lead monitoring technologies can provide a cost-effective and scalable solution for addressing air quality challenges and safeguarding public health and environmental sustainability. Policymakers are encouraged to prioritize investments in WSN infrastructure and capacity-building initiatives to enhance the resilience of air quality monitoring systems and improve regulatory compliance. Communities can benefit from increased access to real-time air quality data, empowering them to make informed decisions about their health and well-being. Environmental scientists have an opportunity to contribute to the development and validation of WSN technologies tailored to local environmental conditions and monitoring needs.

In Nigeria, where air pollution poses significant health risks and environmental challenges, the adoption of WSN-based lead monitoring systems can play a crucial role in mitigating pollution levels and promoting sustainable development. By embracing this innovation, Nigerian stakeholders can leverage the transformative potential of WSNs to address air quality issues, protect public health, and advance environmental management practices in alignment with the Sustainable Development Goals (SDGs), particularly those related to health, sustainable cities, and climate action. Collaborative efforts among government agencies, research institutions, industry stakeholders, and civil society organizations are essential to realize the full benefits of WSN-based lead monitoring and create a cleaner, healthier environment for all Nigerians. Engaging in this endeavour supports Nigeria's commitment to achieving these global targets. Thus, enhancing the quality of life and ensuring environmental sustainability for future generations.

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