FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 8 No. 3, June, 2024, pp 243 - 255
DOI: https://doi.org/10.33003/fjs-2024-0803-2505

ADVANCEMENTS AND INNOVATIONS IN $PM_{2.5}$ MONITORING: A COMPREHENSIVE REVIEW OF EMERGING TECHNOLOGIES

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ABSTRACT

This comprehensive review examines the evolving landscape of $PM_{2.5}$ monitoring, emphasizing its critical role in environmental chemistry, public health and electrical/electronic engineering. Traditional methods, including manual sampling, gravimetric analysis, and the Federal Reference Method (FRM), have long been relied upon for $PM_{2.5}$ measurement but are hindered by limitations in spatial coverage, temporal resolution, and cost. In response, emerging technologies such as wireless sensor networks, low-cost sensor technologies, remote sensing techniques, and machine learning algorithms offer promising solutions to overcome these challenges. Through an analysis of case studies and applications in various environmental settings, including urban areas, industrial zones, and indoor environments, the review highlights the effectiveness of monitoring networks in enhancing spatial and temporal resolution, as well as the need for community engagement and real-time monitoring solutions. Furthermore, technological innovations such as sensor fusion, data analytics, and artificial intelligence hold great promise for improving the accuracy, reliability, and accessibility of $PM_{2.5}$ monitoring data. Regulatory agencies and policymakers play a crucial role in advancing $PM_{2.5}$ monitoring by harmonizing monitoring standards, strengthening quality assurance measures, and developing evidence-based regulations to mitigate air pollution and protect public health. In conclusion, international cooperation and collaboration are essential for addressing transboundary air pollution and global environmental challenges. Regional monitoring networks and international agreements provide frameworks for data sharing, standardization of monitoring practices, and collaborative research efforts. To this end, stakeholders can leverage $PM_{2.5}$ monitoring by adopting new technologies, improving data quality, and supporting evidence-based actions to safeguard public health, the environment, and sustainability.

Keywords: $PM_{2.5}$ pollution, Air quality monitoring, Emerging technologies, Environmental policy, Public health

INTRODUCTION

Particulate matter with a diameter of 2.5 micrometres or smaller, commonly referred to as $PM_{2.5}$, poses a significant environmental health risk that impacts millions worldwide (Yang, Li, & Tang, 2020). These fine particles, originating from various sources, possess the ability to deeply penetrate the human respiratory system, reaching the lungs, and in severe cases, entering the bloodstream, thereby leading to a spectrum of health issues (Yang et al., 2020). Numerous studies have established a link between $PM_{2.5}$ exposure and respiratory infections, aggravated asthma, chronic bronchitis, cardiovascular diseases, and premature mortality (Song et al., 2019; Yuan et al., 2019; Nabizadeh et al., 2019; Thangavel, Park, & Lee, 2022).

The sources of $PM_{2.5}$ pollution are multifaceted, encompassing both anthropogenic and natural activities. Anthropogenic sources include combustion processes such as vehicle emissions, industrial operations, and residential heating, while natural sources comprise wildfires, volcanic eruptions, and dust storms (Huang et al., 2021; Khan et al., 2021; Evangelopoulos et al., 2020). Particularly vulnerable to high $PM_{2.5}$ concentrations are urban and industrialized regions in Asia, Africa, and Latin America, where outdoor air pollution combines with indoor air pollution from the use of solid fuels for cooking and heating, presenting a dual challenge for public health (Gordon et al., 2023; Li et al., 2022).

Monitoring $PM_{2.5}$ pollution plays a critical role in safeguarding public health and the environment, serving as a cornerstone for informed decision-making and effective policy implementation (Sharma et al., 2020). Given the significant health risks associated with $PM_{2.5}$ exposure, accurate and reliable monitoring is imperative for assessing air quality and guiding regulatory actions. Traditional methods of $PM_{2.5}$ monitoring, such as manual sampling, gravimetric analysis, and the Federal Reference Method (FRM), have long served as standard practices (Patel & Aggarwal, 2022). However, these methods often face limitations in spatial coverage, temporal resolution, and cost-effectiveness.

Advancements in technology offer promising solutions to overcome the limitations of traditional methods and enhance $PM_{2.5}$ monitoring capabilities (Fan et al., 2024). Emerging technologies, including wireless sensor networks, low-cost sensor technologies, remote sensing techniques, and machine learning algorithms, provide opportunities for real-time monitoring of $PM_{2.5}$, broader spatial coverage, and improved data accuracy (Mitreska et al., 2023; Yang et al., 2021). These technologies enable the identification of high-risk areas and vulnerable populations, empowering public health authorities to implement targeted interventions and health promotion strategies.

Accurate $PM_{2.5}$ data are indispensable for formulating evidence-based environmental policies and regulatory standards. Epidemiological studies have demonstrated a clear association between $PM_{2.5}$ exposure and adverse health outcomes, providing a compelling rationale for stringent air quality regulations and emission control measures (Dominici et al., 2022). Moreover, $PM_{2.5}$ monitoring contributes to our understanding of pollutant dynamics and informs ecosystem management and conservation efforts by tracking temporal and spatial trends in $PM_{2.5}$ levels (Dominici et al., 2022). Public access to real-time air quality information empowers individuals to make informed decisions about outdoor activities, commute routes, and indoor air quality management practices, thereby reducing personal exposure to harmful pollutants (McCarron et al., 2023). $PM_{2.5}$ monitoring initiatives also raise public awareness about air pollution and its impacts on health and well-being through various communication channels, fostering environmental stewardship and promoting behaviour change (McCarron et al., 2023). Despite the recognized health risks associated with $PM_{2.5}$ exposure and ongoing efforts to monitor and mitigate its presence in the air, challenges persist. These include the need for more comprehensive monitoring networks, especially in low- and middle-income countries, and the development of effective strategies to mitigate emissions from diverse sources.

Therefore, this review aims to comprehensively examine the evolving methodological trends in $PM_{2.5}$ monitoring, encompassing advancements in technology, implications for environmental policy, and public health interventions. The scope of this review encompasses a wide range of topics related to $PM_{2.5}$ monitoring, including traditional methods, emerging technologies, integrated approaches, case studies, challenges, and future directions. By systematically synthesizing relevant literature, this review aims to provide insights into the strengths and limitations of different monitoring techniques, their applications in various settings, and their potential contributions to mitigating $PM_{2.5}$ pollution and its associated health risks.

Review Method

This study employs a systematic and comprehensive approach to identify, select, and analyze relevant literature concerning the evolving methodological trends of $PM_{2.5}$ monitoring. The review initiates with a meticulous literature search across various electronic databases, including PubMed, Web of Science, Scopus, and Google Scholar (Yang et al., 2024). A predefined set of keywords and search terms is utilized to ensure a comprehensive retrieval of literature from peer-reviewed journals, conference proceedings, technical reports, and other pertinent sources. Additionally, manual searches of reference lists of relevant articles and reviews are conducted to identify any additional studies not captured in the initial search.

Inclusion criteria are established to ensure the relevance and quality of the selected studies. These criteria encompass studies focusing on $PM_{2.5}$ monitoring methods, technologies, applications, challenges, and advancements. Both experimental and observational studies, as well as reviews and meta-analyses, are considered for inclusion. Studies are screened based on title, abstract, and full text to determine their eligibility for inclusion in the review. In cases where studies are published in languages other than English, translation is undertaken for inclusion, provided they meet all other eligibility criteria.

Systematic data extraction is performed to capture relevant information from the selected studies. Key data elements extracted include study characteristics (e.g., author, publication year, study design), methodological details (e.g., monitoring techniques, instrumentation), findings, and conclusions. Data synthesis and analysis techniques such as thematic analysis and meta-analysis are employed to derive meaningful insights from the collected data.

To ensure the quality and validity of included studies, a comprehensive quality assessment is conducted using established criteria appropriate for the study design. The quality assessment focuses on methodological rigour, risk of bias, and overall study quality. Studies deemed to have a high risk of bias or methodological limitations are critically appraised, and their findings are interpreted with caution.

This review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to enhance transparency and reproducibility (Prill, et al., 2021). A PRISMA flow diagram is utilized to illustrate the study selection process, and a PRISMA checklist is employed to ensure completeness in reporting.

Traditional Methods of $PM_{2.5}$ Monitoring

$PM_{2.5}$ monitoring has traditionally relied on several established methods, including manual sampling and gravimetric analysis, the Federal Reference Method (FRM), and continuous monitoring stations (Horender et al., 2021). Each method has its own set of principles, advantages, and challenges, which are discussed below:

Manual Sampling and Gravimetric Analysis

Manual sampling and gravimetric analysis represent one of the conventional approaches to $PM_{2.5}$ monitoring. In this method, air samples are collected on filters over a specified duration, and the collected particles are subsequently analyzed gravimetrically to determine $PM_{2.5}$ concentrations according to Twigg et al. (2023) as shown in Figure 1. While manual sampling is relatively simple and cost-effective, it is labour-intensive and time-consuming. Trained personnel are required to operate sampling equipment and process samples in a laboratory setting. The reliance on human intervention introduces potential sources of error and variability, which can affect the accuracy and reliability of results. Factors such as sampler location, sampling duration, and meteorological conditions may influence outcomes, leading to biases and inconsistencies in the data (Twigg et al., 2023).

Moreover, manual sampling lacks real-time monitoring capabilities, as samples need extended periods for collection and subsequent laboratory analysis (Onaiwu & Okuo, 2023). This delay in data collection and analysis may hinder timely responses to changes in air quality and limit the effectiveness of pollution mitigation efforts.

While manual sampling and gravimetric analysis have been pivotal in $PM_{2.5}$ monitoring, their labour-intensive nature, the potential for sampling biases, and lack of real-time monitoring capabilities underscore the need for alternative methods to address current monitoring challenges and improve data accuracy and reliability (Onaiwu & Okuo, 2023).

Figure 1: Set up for the collection of $PM_{2.5}$, Meteorological parameters and the gravimetry determination of the weight of the filter paper (Onaiwu & Efeについては2023; US EPA 2013; Onaiwu & Ifijen 2024).

Federal Reference Method (FRM)

The Federal Reference Method (FRM) is regarded as a cornerstone in $PM_{2.5}$ monitoring, endorsed by regulatory bodies like the United States Environmental Protection Agency (EPA) for its standardized approach (US EPA, 2013). The FRM utilizes automated samplers equipped with size-selective inlet heads and filters to meticulously collect $PM_{2.5}$ samples over a continuous 24-hour period or 8-hour period (Steinle et al., 2015). Subsequently, collected samples undergo gravimetric analysis to ascertain $PM_{2.5}$ concentrations (Onaiwu & Ifijen, 2024).

The structured framework of the FRM ensures consistency and comparability of measurements across diverse monitoring sites, facilitating robust data collection and analysis. This standardized approach has been crucial in providing insights into $PM_{2.5}$ pollution levels, aiding regulatory agencies in formulating evidence-based environmental policies and standards.

However, the implementation of the FRM is not without challenges. Significant infrastructure and resources are required for maintenance and operation, posing a barrier to widespread deployment, especially in resource-limited settings where financial constraints and logistical hurdles may impede accessibility to sophisticated monitoring equipment (Onaiwu & Ifijen, 2024).

Continuous Monitoring Stations

Continuous monitoring stations play a pivotal role in $PM_{2.5}$ monitoring infrastructure, employing real-time instruments such as beta attenuation monitors (BAMs) or tapered element oscillating microbalances (TEOMs) to continuously measure $PM_{2.5}$ concentrations as shown in Figure 2 (Johnston et al., 2023). These stations provide a crucial advantage in terms of temporal resolution and data availability, enabling the detection of short-term variations in $PM_{2.5}$ levels with high precision. By offering real-time data updates, continuous monitoring stations facilitate timely information dissemination to policymakers, public health officials, and the general public, enabling prompt responses to fluctuations in air quality.

Figure 2: E-BAM PLUS Environmental Beta Attenuation Mass Monitor (Johnston et al., 2023)

Despite their utility, continuous monitoring stations face challenges, including substantial installation and maintenance costs. Procuring high-quality instruments and establishing a network of continuous monitoring stations require significant financial investment, limiting widespread deployment, particularly in resource-constrained regions (Wu et al., 2021). Furthermore, maintenance demands ongoing calibration and quality assurance efforts to ensure data accuracy and reliability. Instrument drift, calibration errors, and interference from other airborne particles can compromise station performance, necessitating rigorous monitoring and maintenance protocols to mitigate these issues.

Limitations and Challenges

Manual sampling and gravimetric analysis, despite being traditional methods valued for their simplicity and reliability, encounter several limitations and challenges. These challenges necessitate the consideration of complementary monitoring approaches to address their shortcomings:

Manual Sampling and Gravimetric Analysis: Manual sampling and gravimetric analysis suffer from temporal gaps in data collection due to intermittent sampling, susceptibility to human error, and labour-intensive processes (Twigg et al., 2023). While gravimetric analysis is known for its precision, it is time-consuming and vulnerable to errors from instrumental biases and contamination during sample collection and processing. These limitations underscore the need for alternative monitoring techniques to supplement manual sampling and gravimetric analysis and provide more comprehensive insights into $PM_{2.5}$ pollution dynamics.

Federal Reference Method (FRM): The FRM, endorsed by regulatory agencies for its standardized procedures in $PM_{2.5}$ monitoring, shares similar limitations with manual sampling and gravimetric analysis. These include temporal gaps in data collection and labour-intensive processes (US EPA, 2013). Additionally, the focus on gravimetric analysis may overlook the dynamic nature of $PM_{2.5}$ pollution, highlighting the importance of alternative monitoring techniques to offer a more holistic understanding of air quality.

Continuous Monitoring Stations: While continuous monitoring stations offer real-time data availability and high temporal resolution, they also face challenges. These challenges include high installation and maintenance costs, the need for ongoing calibration and quality assurance efforts, and susceptibility to performance issues such as instrument drift and interference (Johnston et al., 2023). Despite these challenges, continuous monitoring stations remain valuable tools in $PM_{2.5}$ monitoring. Ongoing technological innovation is essential to enhance their precision and reliability and address these challenges effectively.

Emerging Technologies in $PM_{2.5}$ Monitoring

As the demand for more comprehensive and cost-effective $PM_{2.5}$ monitoring solutions grows, emerging technologies have begun to revolutionize the field. These innovative approaches offer advancements in real-time monitoring, spatial coverage, and data accuracy, addressing many of the limitations associated with traditional methods (Montrucchio et al., 2020).

Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) represent an emerging technology that has gained significant attention in recent years for its potential applications in various fields, including environmental monitoring. WSNs consist of spatially distributed sensor nodes equipped with sensing, processing, and communication capabilities, which enable them to collect data from the surrounding environment, process it locally, and transmit it wirelessly to a central node or base station for further analysis (Fascista, 2022).

The introduction of WSNs has revolutionized the way environmental monitoring is conducted, offering several advantages over traditional monitoring approaches. Firstly, WSNs provide a cost-effective and scalable solution for monitoring environmental parameters, including air quality indicators such as $PM_{2.5}$ concentrations. Unlike conventional monitoring stations, which are often expensive to install and maintain, WSNs can be deployed in large numbers across wide geographic areas, providing comprehensive spatial coverage of pollution levels (Fascista, 2022). This scalability makes WSNs particularly well-suited for monitoring air quality in urban areas, industrial zones, and remote locations where traditional monitoring methods may be impractical or cost-prohibitive.

Furthermore, WSNs offer real-time data transmission capabilities, allowing for the continuous monitoring of $PM_{2.5}$ concentrations and the timely dissemination of information to relevant stakeholders. By transmitting data wirelessly, WSNs enable researchers, public health officials, and policymakers to access up-to-date information on air quality conditions, facilitating rapid responses to pollution events or public health emergencies (Fascista, 2022). Real-time data transmission also enhances the accessibility of air quality information to the general public, empowering individuals to make informed decisions about outdoor activities and exposure risks.

In addition to their scalability and real-time capabilities, WSNs offer flexibility in deployment and operation. Sensor nodes can be easily deployed and reconfigured to adapt to changing monitoring needs or environmental conditions, allowing researchers to respond quickly to emerging air quality concerns or events. WSNs can also be integrated with existing infrastructure or deployed as standalone systems, providing versatility in monitoring approaches (Zhu et al., 2021).

WSNs have found numerous applications in $PM_{2.5}$ monitoring, leveraging their advantages to improve the accuracy, coverage, and accessibility of air quality data. One of the primary applications of WSNs in $PM_{2.5}$ monitoring is the establishment of dense monitoring networks in urban areas and industrial zones, where air pollution levels are often elevated due to anthropogenic activities (Zhu et al., 2021). By deploying sensor nodes at strategic locations within these areas, WSNs can provide detailed spatial coverage of $PM_{2.5}$ concentrations, enabling researchers and policymakers to identify pollution hotspots, assess exposure risks, and implement targeted interventions to mitigate air pollution.

Furthermore, WSNs can be used to monitor $PM_{2.5}$ levels in real-time during special events or environmental emergencies, such as wildfires, dust storms, or industrial accidents. By rapidly deploying sensor nodes to affected areas, WSNs can provide timely information on air quality conditions, allowing authorities to issue warnings, implement evacuation measures, and allocate resources to minimize public health impacts (Zhu et al., 2021).

Moreover, WSNs enable community-based monitoring initiatives, empowering citizens to participate in air quality monitoring efforts and raising awareness about environmental issues. By engaging local communities in data collection and analysis, WSNs can foster environmental stewardship and promote individual behaviour change to reduce pollution levels and improve air quality (Zhu et al., 2021).

Low-Cost Sensor Technologies

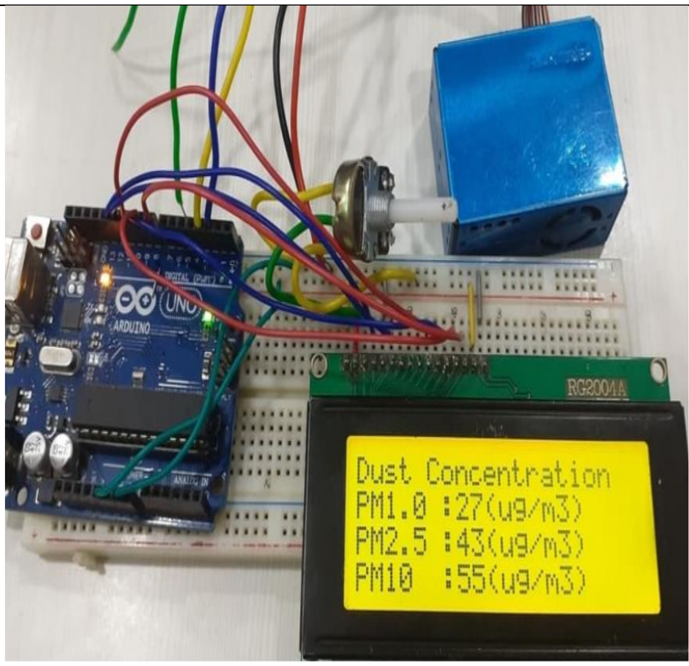
Low-cost sensor technologies have garnered attention as emerging tools for monitoring air quality, including $PM_{2.5}$ concentrations, owing to their affordability, accessibility, and potential for widespread deployment. These sensors offer a cost-effective alternative to traditional monitoring methods, facilitating the creation of dense monitoring networks and enabling individuals, communities, and organizations to access real-time air quality data (Fascista, 2022).

Low-cost sensors for $PM_{2.5}$ monitoring are typically compact, portable devices that utilize optical, electrical, or chemical principles to detect and quantify particulate matter in the air. Examples include the Plantower PMS Series (e.g., Plantower PMS5003 and PMS7003), Nova SDS Series (e.g., SDS011 and SDS018), and PurpleAir PA-II, which employ laser light scattering or other technologies to measure particle concentrations as shown in Figure 3 (Lyu et al., 2024).

*Advantages***:** The affordability, portability, versatility, and real-time data capabilities of low-cost sensors make them advantageous for air quality monitoring. Their cost-effectiveness allows for the creation of dense monitoring networks, providing high spatial resolution data suitable for various applications, including personal exposure monitoring and community-based air quality studies. Additionally, real-time monitoring capabilities enable timely decision-making to reduce exposure to harmful pollutants, while community engagement is fostered by providing access to air quality data.

*Limitations***:** Despite their advantages, low-cost sensors also have limitations. They may exhibit lower accuracy and precision compared to reference-grade instruments, influenced by factors such as sensor drift, cross-sensitivity, and environmental conditions. Calibration and quality assurance procedures for low-cost sensors are often less standardized, posing challenges to data reliability and comparability. Environmental factors such as temperature, humidity, and particle composition may also affect sensor performance and measurement accuracy, while the limited sensor lifespan necessitates frequent replacement or maintenance, increasing overall ownership costs.

(a) Plantower $PM_{2.5}$ Dust Sensor - PMS7003



(b) Interfacing PMS5003 $PM_{2.5}$ Air Quality Sensor with Arduino

(c) PM Sensor SDS011 High Precision $PM_{2.5}$ Air Quality Detection Sensor.

Figure 3: Exploring air quality through the lens of technology: the Plantower PMS7003, interfacing the PMS5003 with Arduino, and the precision of the SDS011 $PM_{2.5}$ sensor.

Remote Sensing Techniques

Remote sensing techniques, such as satellite-based monitoring and unmanned aerial vehicles (UAVs) or drones, provide valuable insights into $PM_{2.5}$ pollution over large geographic areas. Satellite sensors, such as MODIS and VIIRS, offer global coverage and long-term data archives for monitoring trends in $PM_{2.5}$ concentrations (Fascista, 2022). UAVs equipped with specialized sensors can capture high-resolution spatial data on $PM_{2.5}$ levels in real-time, allowing for targeted interventions in areas of concern (Fascista, 2022). These remote sensing techniques complement ground-based monitoring networks and fill gaps in spatial coverage, particularly in regions with limited monitoring infrastructure (Fascista, 2022). A good example of such a sensor is the DSC3013 Infrared Remote Sensing Pavement State Sensor Visibility Transmitter Road Sensor as shown in Figure 4.

Figure 4: DSC3013 Infrared Remote Sensing Pavement State Sensor Visibility Transmitter Road Sensor(Fascista, 2022).

Machine Learning and Artificial Intelligence

Machine learning (ML) and artificial intelligence (AI) algorithms are increasingly being applied to analyze $PM_{2.5}$ monitoring data and predict pollutant concentrations. These techniques can identify complex patterns and correlations in large datasets, enabling more accurate and timely predictions of $PM_{2.5}$ levels. ML models can also integrate data from multiple sources, including meteorological data, land use information, and satellite imagery, to improve the accuracy of $PM_{2.5}$ forecasts and provide early warnings of air quality deterioration (Kothandaraman et al., 2022). The machine learning process is explained with a flow chart as shown in Figure 5.

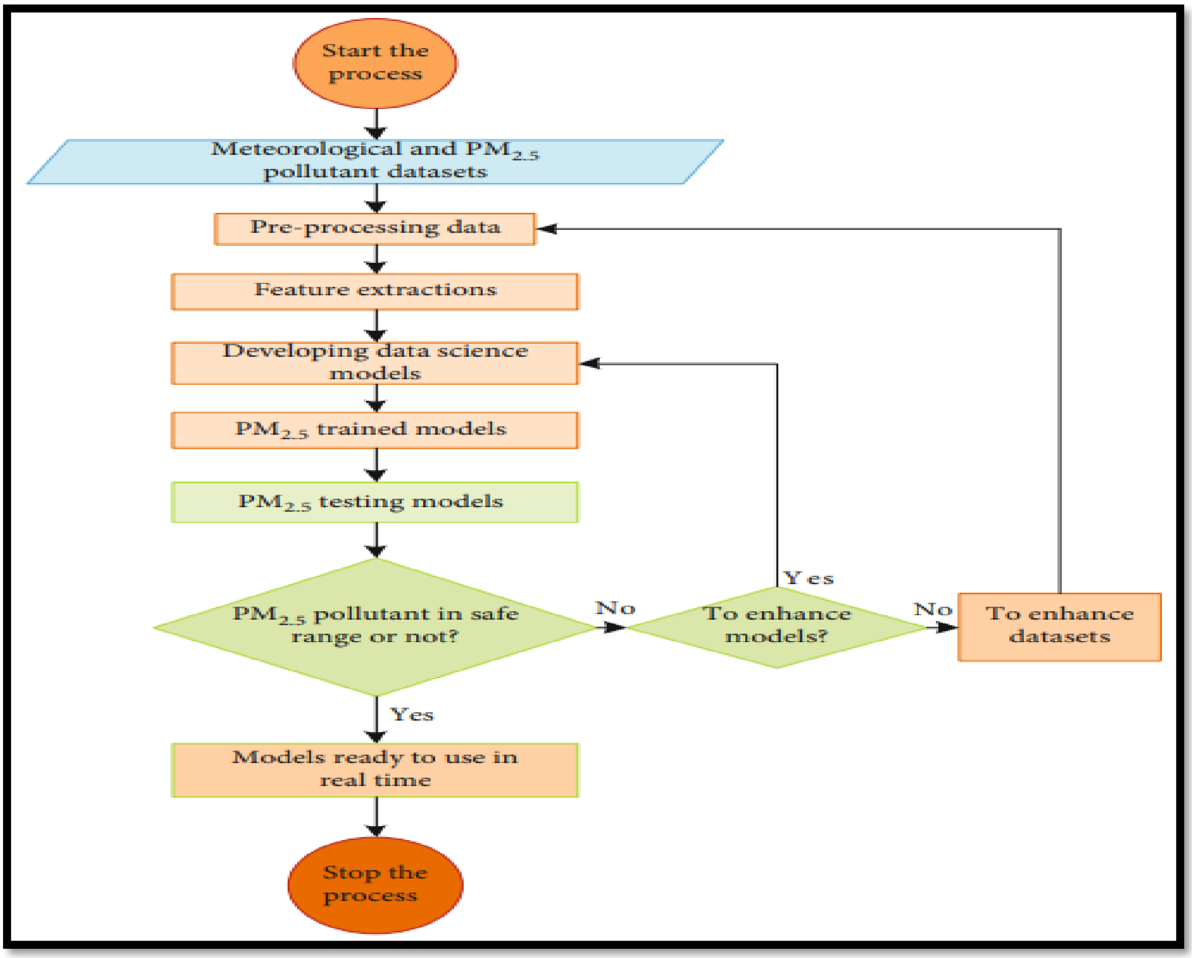


Figure 5: Flowchart representations for predicting $PM_{2.5}$ and air quality forecasting (Kothandaraman et al., 2022)

$PM_{2.5}$ Monitoring with WSNs: Advances, Applications, and Empirical Insights

Wireless Sensor Networks (WSNs) have emerged as a transformative tool for monitoring particulate matter, notably $PM_{2.5}$, in diverse environmental contexts. These networks, equipped with advanced sensor nodes, offer real-time and precise measurements of $PM_{2.5}$ concentrations, thereby contributing significantly to comprehensive air quality assessment and management strategies. By leveraging wireless communication protocols and sophisticated data aggregation techniques, WSNs ensure seamless data transmission from sensor nodes to central servers for analysis and decision-making.

Outdoor Air Quality Monitoring in Industrial and Urban Areas

Mansour et al. (2014) pioneered an outdoor air quality monitoring system tailored for industrialized and urban areas. Their study showcased the use of Zigbee communication technology to sense $PM_{2.5}$ levels effectively. By integrating $PM_{2.5}$ sensors into WSNs, continuous monitoring of particulate pollution became possible, thereby enhancing community awareness and engagement in pollution management efforts.

Indoor Air Quality Monitoring with Low-Cost WSNs

Abraham and Li (2014) introduced a low-cost WSN-based indoor air quality monitoring system. Their solution featured micro gas sensors and XBee modules for simultaneous measurement of multiple air quality parameters, including $PM_{2.5}$. Through this indoor monitoring system, valuable insights into indoor air pollution dynamics were gained, emphasizing the critical role of addressing particulate matter pollution for occupant health and well-being.

Next Generation Air Pollution Monitoring System

Yi et al. (2015) proposed the Next Generation Air Pollution Monitoring System (TNGAPMS), a pioneering initiative leveraging three types of sensor networks to enhance real-time $PM_{2.5}$ monitoring with remarkable cost-effectiveness and spatiotemporal resolution. This conceptual framework laid the groundwork for subsequent advancements in particulate matter monitoring technology, setting a high standard for efficiency and affordability.

Innovative Environmental Sensors in Complex Urban Environments

Kim and his research team implemented an innovative air quality monitoring station within subway systems, focusing on PM_{10} monitoring. Utilizing light scattering methods and linear regression analysis, their study enhanced the accuracy and precision of PM_{10} monitoring. While the focus was on PM_{10}, the study indirectly highlighted the potential of advanced sensor technologies in improving overall air quality monitoring in complex urban environments, which could extend to $PM_{2.5}$ monitoring as well (Kim et al., 2016).

Real-Time Pollution Monitoring in Industrial Areas

Pavani and Rao (2017) deployed WSNs for real-time pollution monitoring in industrial areas, emphasizing the measurement of $PM_{2.5}$ concentrations alongside other gases. Their implementation of multi-hop data aggregation algorithms enabled detailed pollution mapping and efficient data dissemination, offering valuable insights for pollution management and mitigation strategies.

Urban $PM_{2.5}$ Monitoring Across Multiple Layers of City Infrastructure

Ahuja et al. (2016) introduced novel approaches to urban $PM_{2.5}$ monitoring by deploying WSNs across multiple layers of a city's infrastructure. This deployment significantly improved the spatial resolution of $PM_{2.5}$ data, enabling more accurate urban pollution mapping. The study sheds light on the complexities of urban air quality dynamics and underscores the importance of high-resolution monitoring for effective pollution management.

Predictive PM2.5 Monitoring Using Machine Learning

Gupta and Jha (2018) developed a WSN system equipped with advanced machine-learning algorithms to predict $PM_{2.5}$ concentration levels based on historical and real-time data. By leveraging machine learning techniques, the system facilitated proactive air quality management in industrial zones, enabling timely interventions to mitigate pollution levels and protect public health.

Precision Agriculture Through Greenhouse PM2.5 Monitoring

Fascista (2022) implemented a WSN-based system in greenhouse environments to monitor and control $PM_{2.5}$ levels for optimal plant growth. This study demonstrated the utility of WSNs in precision agriculture, highlighting the potential for sensor-based monitoring to optimize growing conditions and improve agricultural productivity.

Integration of LPWAN Technologies for Remote $PM_{2.5}$ Monitoring

Camarillo et al. (2022) focused on integrating low-power wide-area network (LPWAN) technologies with WSNs for $PM_{2.5}$ monitoring in remote environments. By extending the operational range and battery life of sensor nodes, this integration enables effective $PM_{2.5}$ monitoring in areas where traditional communication networks may be limited or unavailable.

Securing Data Transmission with Blockchain in WSNs

Shen and his research team explored the use of blockchain technology for securing data transmission in WSNs used for $PM_{2.5}$ monitoring. By ensuring the integrity and confidentiality of sensitive environmental data, blockchain technology enhances the reliability and trustworthiness of WSN-based monitoring systems, addressing concerns related to data tampering and unauthorized access (Shen et al., 2023)

Energy-Efficient Sensor Node Designs Through Novel Energy Harvesting Techniques

Sassi and Fourati (2023) developed energy-efficient sensor node designs using novel energy-harvesting techniques. By harnessing ambient energy sources, these sensor nodes can operate indefinitely without the need for battery replacement, ensuring continuous $PM_{2.5}$ monitoring with minimal maintenance requirements.

AI-Driven Anomaly Detection for Early Identification of $PM_{2.5}$ Spikes

Scarlatache et al. (2023) introduced AI-driven anomaly detection algorithms in WSNs for early identification of abnormal $PM_{2.5}$ spikes in urban environments. By enhancing the responsiveness of emergency services to environmental hazards, these algorithms improve public safety and contribute to effective disaster management strategies.

Comprehensive Review of WSN Advancements for $PM_{2.5}$ Monitoring

Workman et al. (2024) presented a comprehensive review of advancements in WSN technology for $PM_{2.5}$ monitoring. Emphasizing improvements in sensor accuracy, network reliability, and data processing capabilities, the review highlights the progress made in the field while also acknowledging the remaining challenges in scalability and sensor miniaturization.

Table 1: Summary of $PM_{2.5}$ Monitoring Techniques, Case Studies, and Findings

Reference	Monitoring Technique	Deployment Details	Case Study Description	Key Findings
Mansour et al. (2014)	Zigbee communication technology	Tailored for industrialized and urban areas	Outdoor air quality monitoring system	Continuous monitoring of particulate pollution, enhancing community awareness
Abraham and Li (2014)	Micro gas sensors, XBee modules	Low-cost indoor air quality monitoring system	Simultaneous measurement of multiple air quality parameters	Insights into indoor air pollution dynamics, the importance of addressing $PM_{2.5}$
Yi et al. (2015)	Three types of sensor networks	Cost-effective and high-resolution $PM_{2.5}$ monitoring	Next Generation Air Pollution Monitoring System (TNGAPMS)	Pioneering initiative laying the groundwork for advancements in $PM_{2.5}$ monitoring technology
Kim et al. (2016)	Light scattering methods, linear regression analysis	Monitoring stations within subway systems	Focus on PM10 monitoring	Indirect insights into overall air quality monitoring in complex urban environments
Pavani and Rao (2017)	Multihop data aggregation algorithms	Real-time pollution monitoring in industrial areas	Measurement of $PM_{2.5}$ concentrations alongside other gases	Detailed pollution mapping, efficient data dissemination

Reference	Monitoring Technique	Deployment Details	Case Study Description	Key Findings
Ahuja et al. (2016)	Deployment across multiple layers of city infrastructure	Urban $PM_{2.5}$ monitoring	Improved spatial resolution of $PM_{2.5}$ data	Enhanced urban pollution mapping, better pollution management
Gupta and Jha (2018)	Advanced machine learning algorithms	Proactive air quality management in industrial zones	Prediction of $PM_{2.5}$ concentration levels	Facilitated proactive interventions, improved public health outcomes
Fascista, 2022	WSN-based system in greenhouse environments	$PM_{2.5}$ monitoring for optimal plant growth	Precision agriculture application	Utility of WSNs in optimizing growing conditions
Camarillo et al. (2022)	Integration of LPWAN technologies	Remote $PM_{2.5}$ monitoring	Extending operational range and battery life of sensor nodes	Effective $PM_{2.5}$ monitoring in remote areas
Shen et al. (2023)	Blockchain technology for securing data transmission	WSNs used for $PM_{2.5}$ monitoring	Ensuring integrity and confidentiality of environmental data	Enhanced reliability and trustworthiness of monitoring systems
Sassi and Fourati (2022)	Energy harvesting techniques	Energy-efficient sensor node designs	Indefinite operation of sensor nodes without battery replacement	Continuous $PM_{2.5}$ monitoring with minimal maintenance
Scarlatache et al. (2023)	AI-driven anomaly detection algorithms	WSNs for early identification of abnormal $PM_{2.5}$ spikes	Enhancing responsiveness of emergency services	Improved public safety, effective disaster management
Workman et al. (2024)	Review of advancements in WSN technology	$PM_{2.5}$ monitoring	Comprehensive review of sensor accuracy, network reliability, and data processing capabilities	Progress in the field, challenges in scalability and sensor miniaturization

The evolution of Wireless Sensor Networks (WSNs) in monitoring particulate matter, specifically $PM_{2.5}$, represents a significant advancement in environmental chemistry, public health, and telecommunication engineering. From the introduction of the Next Generation Air Pollution Monitoring System (TNGAPMS) by Yang, Li, and Tang (2020) in 2015 to the comprehensive review by Mitreska et al. (2023) in 2024, nearly a decade encapsulates innovation, challenges, and achievements in this field. Early developments by researchers like Yang, Li, and Tang (2020) and Mansour et al. (2014) laid the groundwork for $PM_{2.5}$ monitoring, emphasizing cost-effectiveness, real-time data acquisition, and the use of Zigbee communication technology. These pioneering efforts aimed at enhancing spatial and temporal resolution in air quality monitoring, setting a benchmark for subsequent research.

The introduction of low-cost indoor air quality monitoring systems expanded the application domain of WSNs, underlining the significance of indoor air quality surveillance (Abraham and Li, 2014). Meanwhile, the versatility of WSNs was showcased in different environments, from subways to industrial zones, demonstrating the adaptability and potential of sensor technologies in environmental health (Kim et al., 2016).

Subsequent years witnessed rapid advancements in WSN technology for $PM_{2.5}$ monitoring. Innovations introduced novel urban monitoring strategies, leveraging machine learning for enhanced data accuracy and proactive pollution management (Fan et al., 2024). The application of WSNs in precision agriculture illustrated the versatility of sensor networks beyond traditional environmental monitoring. Moreover, the integration of low-power wide-area network (LPWAN) technologies and blockchain addressed challenges in operational range, battery life, and data security (Gupta and Jha, 2018).

The latest research introduces energy-efficient sensor designs and AI-driven anomaly detection algorithms, indicating a shift towards sustainable, smart monitoring solutions capable of self-sustaining operation and early hazard identification (Fascista, 2022). Reflecting on these advancements, improvements in sensor accuracy, network reliability, and data processing capabilities have been acknowledged. However, unresolved challenges in scalability and sensor miniaturization suggest areas for future research.

Comparing early studies with advancements reveals a trajectory of innovation driven by technological advancements and expanding application domains. Initial efforts established foundational principles of WSN-based $PM_{2.5}$ monitoring, while recent developments have pushed the boundaries of what's possible, incorporating advanced computational methods, energy harvesting, and AI algorithms into WSN design and operation. This evolution reflects a broader trend towards more intelligent, autonomous, and versatile sensor networks in environmental monitoring. Despite remarkable progress, the journey of WSNs in $PM_{2.5}$ monitoring is far from complete. Future research must address remaining challenges in scalability, energy efficiency, and sensor miniaturization to fully realize the potential of WSNs in safeguarding environmental health and human well-being.

Challenges and Future Directions in $PM_{2.5}$ Monitoring

PM2.5 monitoring is pivotal in informing environmental policies and safeguarding public health, providing critical data that guide the formulation of evidence-based regulations and interventions. In the United States, agencies such as the Environmental Protection Agency (EPA), along with the European Environment Agency (EEA) in Europe, depend on robust $PM_{2.5}$ monitoring networks. These networks assess compliance with air quality standards and identify areas where improvements are needed. This invaluable data supports policy decisions around emission controls, urban development, and transportation planning—key factors in reducing air pollution and enhancing public health.

Moreover, the insights gained from $PM_{2.5}$ monitoring are essential for orchestrating targeted public health interventions. These efforts aim to reduce exposure to harmful pollutants and mitigate the associated health risks. Elevated $PM_{2.5}$ levels are linked to serious health issues, including respiratory and cardiovascular diseases, lung cancer, and premature death. Timely information on $PM_{2.5}$ concentrations enables public health authorities to issue warnings, implement pollution reduction measures, and promote behaviour changes to minimize exposure, especially in vulnerable groups such as children, the elderly, and those with pre-existing health conditions.

Additionally, $PM_{2.5}$ monitoring plays a crucial role in addressing environmental justice and equity. It helps to identify disparities in air pollution exposure across different demographics and communities. Studies have shown that low-income and minority communities often experience higher levels of $PM_{2.5}$ pollution due to their proximity to industrial sites, major roads, and waste facilities. By leveraging $PM_{2.5}$ data, policymakers can pinpoint environmental justice hotspots, guiding targeted actions to alleviate pollution burdens and improve environmental quality in these marginalized areas.

International collaboration is also vital in tackling transboundary air pollution and global environmental challenges. Networks such as the European Air Quality Monitoring Network (AQMN) and the Asian Dust Network (ADN) facilitate the sharing of data, standardization of monitoring techniques, and cooperative research efforts. Agreements like the Convention on Long-Range Transboundary Air Pollution (LRTAP), under the aegis of the United Nations Economic Commission for Europe (UNECE), exemplify the global commitment to reducing emissions of $PM_{2.5}$ and other pollutants, protecting human health and the environment across borders.

CONCLUSION

This comprehensive review underscores the pivotal role of $PM_{2.5}$ monitoring in environmental science, electronic/telecommunication engineering and public health. By delving into the methodological trends, including both traditional techniques and emerging technologies, along with their practical applications, case studies, and implications for environmental policy and public health, we've gained valuable insights into the state of $PM_{2.5}$ monitoring. While traditional methods like manual sampling, gravimetric analysis, and the Federal Reference Method (FRM) have been longstanding standards for $PM_{2.5}$ measurement, their limitations in spatial coverage, temporal resolution, and cost are evident. However, emerging technologies, such as wireless sensor networks, low-cost sensor technologies, remote sensing techniques, and machine learning algorithms, offer promising avenues to overcome these limitations and enhance $PM_{2.5}$ monitoring capabilities. In particular, technological innovations like sensor fusion, data analytics, and artificial intelligence show significant promise in improving the accuracy, reliability, and accessibility of $PM_{2.5}$ monitoring data. Moreover, collaboration between regulatory agencies and policymakers is essential to harmonize monitoring standards, strengthen quality assurance measures, and develop evidence-based regulations to mitigate air pollution and safeguard public health.

International cooperation is crucial in addressing transboundary air pollution and global environmental challenges. Networks like the European Air Quality Monitoring Network (AQMN) and the Asian Dust Network (ADN) facilitate data sharing, standardization of monitoring practices, and collaborative research efforts on a regional and global scale. Furthermore, international agreements such as the Convention on Long-Range Transboundary Air Pollution (LRTAP) provide a framework for nations to collaborate in reducing emissions of air pollutants, including $PM_{2.5}$, to protect human health and the environment.

In the face of unprecedented environmental challenges, including climate change, biodiversity loss, and air pollution, concerted action is urgently needed to safeguard our planet and ensure a sustainable future. $PM_{2.5}$ monitoring plays a vital role in this endeavour, providing actionable information to policymakers, public health officials, and the general public to address air pollution risks and promote environmental sustainability.

In low-income countries like Nigeria, embracing and investing in $PM_{2.5}$ monitoring infrastructure, advancing monitoring technologies, and strengthening regulatory frameworks are critical steps toward creating cleaner, healthier, and more resilient communities. The evolving approach to $PM_{2.5}$ monitoring is a dynamic and interdisciplinary field that demands continuous innovation, collaboration, and commitment from all involved. We can harness the power of $PM_{2.5}$ monitoring by leveraging emerging technologies, improving data quality and reliability, and promoting evidence-based policies and interventions. This will help protect public health, preserve environmental quality, and build a more sustainable future.

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