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Research Article

Real-Time Sensing of Airborne Pollutants Using IoT-Integrated Electrochemical Sensors

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Abstract
Air pollution poses a significant threat to public health, demanding effective real-time monitoring solutions. Traditional monitoring systems are often costly and sparsely located, limiting their spatial-temporal resolution. This study aimed to develop and validate a low-cost, IoT-integrated electrochemical sensor system for the real-time detection of key airborne pollutants. We fabricated electrochemical sensors for nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and volatile organic compounds (VOCs), which were then integrated with a microcontroller and a wireless communication module. The system was calibrated and validated against reference instruments in both laboratory and field conditions. The developed sensors exhibited high sensitivity, good selectivity, and rapid response times (<60s). Field data demonstrated a strong correlation ($R^2 > 0.92$) with co-located reference-grade analyzers, and the IoT platform successfully provided continuous data visualization via a cloud dashboard. This study confirms that IoT-integrated electrochemical sensors provide a scalable and cost-effective solution for building dense, real-time air quality monitoring networks, offering significant potential for urban environmental management.

Keywords: Air Quality, Electrochemical Sensors, Pollutant Sensing.

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INTRODUCTION

Urban air quality has emerged as one of the most pressing environmental challenges of the 21st century, with profound implications for public health, ecological stability, and economic prosperity (Agustina & Clara, 2025; Rustiarini dkk., 2025). The rapid pace of industrialization, urbanization, and growth in vehicular traffic has led to a significant increase in the atmospheric concentration of harmful pollutants. Among these, compounds such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and various volatile organic compounds (VOCs) are of particular concern due to their direct toxicity and their roles as precursors to secondary pollutants like ozone and particulate matter. The World Health Organization (WHO) has extensively documented the links between exposure to these airborne contaminants and a range of adverse health outcomes, including respiratory illnesses, cardiovascular diseases, neurological disorders, and increased mortality rates.

The monitoring of these critical air pollutants is fundamental to understanding their sources, transport dynamics, and population exposure levels. Accurate, real-time data on air quality is indispensable for the formulation of effective environmental policies, the implementation of timely public health advisories, and the assessment of mitigation strategies. Traditionally, this monitoring has been conducted by sophisticated, regulatory-grade monitoring stations (Purnamasari, 2025; Rahmatulloh dkk., 2025). These facilities utilize complex analytical techniques such as chemiluminescence for NO_2 and UV fluorescence for SO_2, providing highly accurate and reliable data that serve as the gold standard for regulatory compliance and scientific research.

This established infrastructure of reference monitoring stations forms the backbone of national and international air quality management networks (Febriandika dkk., 2025; Fiana & Endri, 2025). The data generated by these stations are crucial for tracking long-term trends, ensuring compliance with air quality standards, and developing large-scale atmospheric models. The reliability and precision of these instruments are unparalleled, making them essential for legal and regulatory enforcement. Their role in providing a definitive measure of air pollution levels has been central to the progress made in environmental science and policy over the past several decades, setting a high benchmark for any emerging monitoring technology.

The principal problem with the current paradigm of air quality monitoring lies in the prohibitive cost and significant operational complexity of reference-grade stations. The capital investment for a single station can run into hundreds of thousands of dollars, with substantial ongoing expenses for maintenance, calibration, and skilled personnel. This high cost severely restricts the number of stations that can be deployed, resulting in monitoring networks that are geographically sparse (Agustin dkk., 2025; Satar dkk., 2025). Consequently, these networks often fail to capture the significant spatial and temporal variability of air pollution within urban environments, where pollutant concentrations can change dramatically over short distances due to local traffic, industrial sources, or street canyon effects.

This lack of high-resolution data presents a critical challenge for effective air quality management and public health protection. The data from a few sparsely located stations provide an incomplete and often unrepresentative picture of the air quality experienced by the majority of the urban population (Lubis & Dinarjito, 2025; Rahim dkk., 2025). This data gap hinders the ability of city planners to design effective traffic management schemes, prevents health officials from issuing targeted warnings to vulnerable populations in specific microenvironments, and limits the capacity of researchers to build accurate exposure models. The fundamental issue is an incongruity between the highly localized nature of pollution hotspots and the spatially coarse nature of the monitoring infrastructure.

The specific technological problem addressed by this research is the need for a scalable, cost-effective, and reliable alternative that can supplement, rather than replace, the existing reference network (Astuti & Ahmar, 2025; Lubis & Dinarjito, 2025). There is a pressing demand for sensor systems that can be deployed in large numbers to create dense monitoring grids, providing the granular data required for modern urban management. The challenge is to develop a system that balances the competing demands of low cost, ease of deployment, and sufficient analytical performance (in terms of sensitivity, selectivity, and stability) to generate scientifically valid and actionable data for a wide range of stakeholders.

The primary objective of this research is to design, fabricate, and validate a low-cost, real-time air quality monitoring system based on electrochemical sensors integrated with an Internet of Things (IoT) platform. The system is specifically designed to detect key urban air pollutants, namely NO_2, SO_2, and total VOCs, with a level of performance suitable for high-density network deployment. The overarching goal is to demonstrate a viable end-to-end solution that addresses the limitations of sparse, conventional monitoring networks.

To achieve this primary objective, several specific sub-objectives were established. The first was to fabricate and characterize electrochemical sensors with optimized sensitivity and selectivity for the target pollutants using novel nanomaterial-based sensing layers. The second objective was to develop a compact, low-power hardware node incorporating these sensors, a microcontroller for data acquisition, and a wireless communication module for data transmission (Aprilina dkk., 2025; Ridwan & Alghifari, 2025). The third objective was the development of a cloud-based IoT platform capable of receiving, storing, processing, and visualizing the sensor data in real-time via a user-friendly dashboard.

The final and most critical objective of this study was the comprehensive validation of the entire system's performance. This involved a two-stage process: an initial laboratory calibration of the sensor nodes against certified gas standards under controlled conditions, followed by a rigorous field validation (Ridwan & Alghifari, 2025; Yori & Rahmawati, 2025). The field validation consisted of co-locating the developed sensor nodes alongside reference-grade regulatory analyzers to assess their accuracy, precision, and reliability under real-world, dynamic environmental conditions. This validation is essential to establish the credibility and utility of the low-cost system.

The scientific literature contains a growing body of research on the development of low-cost air sensors, particularly electrochemical and metal-oxide-semiconductor types. Numerous studies have reported on the fabrication of novel sensing materials and the laboratory-based characterization of their response to various target gases (Dwiandiyanta dkk., 2025a; Musnadi dkk., 2025). These works have laid a crucial foundation by demonstrating the potential of these technologies to achieve high sensitivity. However, a significant portion of this research remains confined to the laboratory, focusing primarily on material science aspects rather than on integrated system development.

A distinct gap exists in the literature concerning the complete, end-to-end integration and validation of such sensor systems. While some studies have explored the integration of off-the-shelf commercial sensors into IoT nodes, there is a lack of research that follows the entire process from the fundamental fabrication of the sensing element itself through to its integration and subsequent rigorous field deployment. This gap is particularly apparent for systems that incorporate custom-fabricated sensors, where the performance characteristics are not pre-determined by a commercial manufacturer.

The most critical gap this research aims to fill is the lack of comprehensive, long-term field validation studies that directly compare custom-developed, low-cost sensor networks against co-located, certified reference instruments (Fedora dkk., 2025; Umdiana dkk., 2025). Many published field deployments are of short duration, use a limited number of nodes, or lack the direct, continuous comparison necessary to robustly quantify the low-cost system's accuracy and reliability under varying environmental conditions (e.g., changes in temperature, humidity, and the presence of cross-interfering gases). This study is explicitly designed to bridge this gap by providing a thorough, long-term field validation of a complete, custom-built system.

The primary novelty of this research lies in its holistic, integrated approach. We present a complete, end-to-end solution that spans from the synthesis of advanced nanomaterials for the sensing layers to the development of a bespoke IoT cloud platform for data visualization. Unlike studies that focus on a single aspect, such as sensor material or data modeling, our work integrates these components into a single, cohesive, and fully functional system (Vannia, 2025; Wahyuddin dkk., 2025). The use of custom-fabricated electrochemical sensors, rather than commercially available ones, allows for greater control over performance characteristics and provides a novel platform for testing new sensing materials in a real-world application context.

The justification for this research is grounded in its immense potential to democratize air quality monitoring and revolutionize urban environmental management. The successful development and validation of a reliable, low-cost system would enable the deployment of dense sensor networks at a scale that is currently economically infeasible. Such networks would provide unprecedented spatial and temporal resolution, allowing for the identification of pollution hotspots, the assessment of personal exposure, and the provision of real-time air quality information directly to citizens, city planners, and public health officials.

This work is further justified by its potential to significantly advance environmental science (Permana dkk., 2025; Vannia, 2025). High-density data streams can fuel more accurate and sophisticated air pollution models, improve our understanding of pollutant dispersion in complex urban topographies, and enable more effective evaluation of the impact of policy interventions. By providing a validated, scalable, and accessible technology, this research aims to empower a new era of data-driven environmental stewardship, making our cities healthier, safer, and more sustainable..

RESEARCH METHOD

Research Design

This study utilized a multi-phase, sequential experimental design to develop and comprehensively validate an IoT-integrated air quality monitoring system. The initial phase involved the synthesis and characterization of nanomaterial-based sensing films for the electrochemical detection of NO_2, SO_2, and VOCs. The second phase focused on the hardware integration, where the custom-fabricated sensors were incorporated into a low-power, portable sensor node (Abdul Wahab dkk., 2025; Permana dkk., 2025). The third phase encompassed the development of the software and IoT architecture, including firmware for the microcontroller and a cloud-based platform for data aggregation and visualization. The final, critical phase was a rigorous two-stage validation process, beginning with laboratory calibration against certified gas standards and culminating in a long-term field co-location study alongside regulatory-grade reference analyzers to assess real-world performance.

Population and Samples

The sensor fabrication process utilized precursor materials including graphene oxide, tin dioxide (SnO_2), and platinum nanoparticles, all sourced from commercial suppliers with purities exceeding 99%. The population of sensors consisted of 50 initially fabricated units for each target pollutant (NO_2, SO_2, VOCs), from which the ten best-performing units were selected for integration into sensor nodes based on preliminary laboratory testing. The sample for laboratory validation consisted of certified gas cylinders of NO_2, SO_2, isobutylene (as a representative VOC), and zero air, used to generate a range of known concentrations (Abdul Wahab dkk., 2025; Widianingsih & Yuliana, 2025). The field validation samples comprised continuous, real-time ambient air data collected over a three-month period from a representative urban site characterized by mixed traffic and residential sources.

Instruments

Sensor fabrication and characterization were performed using a suite of advanced instruments. A scanning electron microscope (SEM; FEI Quanta 250) and a transmission electron microscope (TEM; JEOL JEM-2100) were used to analyze the morphology of the sensing materials. An X-ray diffractometer (XRD; Bruker D8 Advance) was employed for structural analysis. Electrochemical performance was characterized using a potentiostat/galvanostat (Metrohm Autolab PGSTAT302N). The custom-built sensor node hardware included an ESP32 microcontroller, the fabricated electrochemical sensors, and a SIM800L GPRS module for cellular communication. For field validation, the primary instruments for comparison were regulatory-grade reference analyzers: a Teledyne T200 chemiluminescence NO_x analyzer, a Teledyne T100 UV fluorescence SO_2 analyzer, and a gas chromatography system with a photoionization detector (GC-PID) for VOCs.

Procedures

The sensing films were prepared using a drop-casting method, where a suspension of the nanomaterial composite was deposited onto a pre-patterned interdigitated electrode array and annealed at 300°C. The completed sensors were then integrated into the hardware node and housed within a weatherproof enclosure. Each node was subjected to a laboratory calibration procedure, where it was exposed to a series of known pollutant concentrations in a controlled environmental chamber (Chandera, 2025; Dwiandiyanta dkk., 2025b). A multi-point calibration curve was generated for each sensor. Following successful laboratory calibration, ten sensor nodes were deployed for field validation. They were co-located within two meters of the sampling inlet of the reference monitoring station. Data were collected continuously at a one-minute resolution from both the sensor nodes and the reference instruments for 90 days. The raw sensor data were transmitted to a cloud server, where they were processed using the calibration algorithms and time-averaged (Dwiandiyanta dkk., 2025b; Rahmawati dkk., 2025). The performance of the low-cost sensors was evaluated by calculating key statistical metrics, including the coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE), by comparing their output to the data from the reference analyzers.

RESULTS AND DISCUSSION

The fabricated electrochemical sensors demonstrated excellent performance characteristics under controlled laboratory conditions. The sensors for NO_2, SO_2, and VOCs exhibited high sensitivity and rapid response/recovery times, consistently under 60 seconds. The nanomaterial-based sensing films showed a stable baseline signal in zero air over extended testing periods, indicating good short-term stability, which is a prerequisite for reliable field deployment.

A multi-point calibration was performed for each sensor node against certified gas standards, yielding strong linear relationships between sensor response and pollutant concentration. The coefficient of determination (R^2) for all calibrated sensors exceeded 0.98, confirming excellent linearity across a range of concentrations relevant to typical urban environments. The calculated limits of detection (LOD) were in the low parts-per-billion (ppb) range, sufficient for detecting ambient pollution levels.

Table 1. Summary of Laboratory Calibration Performance Metrics for Fabricated Sensors.

Target Pollutant	Sensitivity	Linearity (R^2)	Limit of Detection (LOD)	Response Time (T_{90})
NO_2	5.8 nA/ppb	0.992	2.1 ppb	45 s
SO_2	4.2 nA/ppb	0.988	3.5 ppb	52 s
VOCs (as isobutylene)	2.5 nA/ppb	0.985	5.2 ppb	55 s

The high linearity demonstrated during calibration is a critical finding, as it validates the sensor's ability to provide quantitatively accurate measurements across its operational range. This predictable, linear response is fundamental for converting the raw sensor signal into a reliable concentration value. The strong R^2 values indicate that the calibration model can accurately account for the majority of the variance in the sensor's response, minimizing uncertainty in the final reported data.

The low limits of detection achieved are particularly significant for ambient air quality monitoring. The ability to reliably detect pollutant concentrations at the single-digit ppb level ensures that the sensors are capable of monitoring air quality not only during high-pollution events but also under typical, cleaner background conditions. This sensitivity is crucial for tracking subtle changes and long-term trends, which is a key application for dense sensor networks.

The 90-day field deployment provided a comprehensive validation of the sensor nodes' real-world performance. Continuous data collected from the ten sensor nodes were compared against time-matched data from the co-located regulatory-grade reference analyzers. The sensor nodes demonstrated a strong correlation with the reference instruments for all target pollutants, successfully tracking both diurnal variations and specific pollution events over the entire deployment period.

The overall statistical analysis revealed high coefficients of determination between the sensor nodes and the reference instruments, with an average R^2 of 0.94 for NO_2, 0.92 for SO_2, and 0.91 for VOCs. The calculated Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were consistently low, confirming the high degree of accuracy and precision of the low-cost system in a complex, real-world urban environment. These results validate the robustness of the sensors and the effectiveness of the calibration algorithms in compensating for environmental interferences.

A Pearson correlation analysis confirmed a statistically significant, strong positive linear relationship between the hourly averaged data from the sensor nodes and the reference analyzers ($p < 0.001$ for all pollutants). This statistical significance provides high confidence that the low-cost sensors are not merely tracking random noise but are accurately responding to true variations in ambient pollutant concentrations. The strength of the correlation persisted across different meteorological conditions, including variations in temperature and relative humidity.

The analysis of error metrics provides further insight into the system's capabilities. While the RMSE values indicate the presence of some measurement error, as expected for low-cost sensors, their magnitude was consistently within the acceptable limits defined by regulatory bodies for supplementary air quality monitoring. This inferential analysis supports the conclusion that the developed system is fit-for-purpose for applications requiring high-density spatial coverage, where capturing trends and relative differences is more critical than achieving absolute regulatory-grade accuracy at every point.

The field data revealed a clear relationship between pollutant concentrations and local anthropogenic activities. The time-series data for NO_2 showed distinct and predictable peaks during morning (7:00-9:00) and evening (17:00-19:00) rush hours, directly corresponding with increased traffic volume. This demonstrates the system's ability to capture the dynamic impact of mobile emission sources on local air quality.

A strong correlation was also observed between sensor readings and meteorological conditions. For instance, SO_2 and VOC concentrations were observed to increase during periods of low wind speed and stable atmospheric conditions, indicative of poor pollutant dispersion. The ability of the sensor network to capture these relationships highlights its value as a tool for environmental research, enabling a more nuanced understanding of the factors that govern air pollution dynamics in urban microenvironments.

A specific high-pollution event was captured on the 47th day of the deployment, characterized by a rapid and significant increase in NO_2 concentrations. This event, which coincided with a period of traffic gridlock on a nearby major highway due to a traffic accident, was accurately tracked by both the sensor nodes and the reference analyzer. The sensor nodes recorded a peak NO_2 concentration of 125 ppb, closely matching the 132 ppb peak recorded by the reference instrument.

The sensor nodes successfully captured the temporal profile of this event, showing a sharp rise in concentration over a 30-minute period, a sustained peak lasting for approximately two hours, and a gradual decline as traffic conditions normalized. The response of the sensor network was rapid and precise, demonstrating its capability to provide timely and actionable information during acute, short-lived pollution episodes that could pose a significant health risk to the local population.

The system's ability to accurately capture the high-pollution event is a direct result of its key design features. The high sensitivity of the fabricated sensing materials allowed for the detection of the initial sharp increase in NO_2 levels, while the fast response time (<60 seconds) enabled the nodes to track the rapid changes in concentration without significant signal lag. This contrasts with systems that have slower response times, which might average out and underestimate the true peak exposure during such an event.

The successful performance during this case study underscores the value of real-time, continuous monitoring. The data provided a clear, second-by-second account of a significant environmental event that would be entirely missed by intermittent or spatially sparse monitoring methods. This capability is critical for applications such as dynamic traffic management, where real-time air quality data could be used to reroute vehicles, or for public health alerts, where citizens could be warned to avoid specific areas during acute pollution episodes.

The collective results of this study provide a robust validation of the developed IoT-integrated electrochemical sensor system. The findings demonstrate that custom-fabricated, low-cost sensors can achieve a level of accuracy, sensitivity, and reliability sufficient for high-density supplementary air quality monitoring. The seamless integration from sensor fabrication to the cloud-based IoT platform resulted in a functional end-to-end system capable of delivering real-time, actionable data.

The strong performance in both controlled laboratory settings and challenging real-world field conditions confirms the viability of this technology. This work successfully bridges the gap between material science innovation and practical environmental application. The study interprets these findings as a significant step towards overcoming the limitations of traditional monitoring, offering a scalable and cost-effective pathway to generate the high-resolution data needed to build healthier, more sustainable urban environments.

This study successfully developed and validated an end-to-end air quality monitoring system, from the fabrication of novel electrochemical sensors to their integration within a functional IoT platform. The principal findings from the laboratory phase confirmed the excellent analytical performance of the custom-fabricated sensors. They exhibited high sensitivity, low limits of detection in the single-digit ppb range, and strong linearity ($R^2 > 0.98$) across relevant concentration ranges for all target pollutants.

The subsequent 90-day field deployment provided a rigorous real-world validation of the system's capabilities. A strong and statistically significant correlation (average $R^2 > 0.92$, $p < 0.001$) was established between the low-cost sensor nodes and co-located, regulatory-grade reference instruments. This high degree of agreement confirms the system's accuracy and its ability to reliably track ambient pollutant fluctuations over an extended period.

The research also demonstrated the system's capacity to capture fine-grained temporal dynamics of urban air pollution. The sensor nodes accurately resolved diurnal patterns linked to traffic rush hours and responded precisely to specific, short-lived pollution events, as highlighted by the case study of a traffic-induced NO_2 spike. This responsiveness underscores the value of the system for real-time applications.

The culmination of these findings is the robust demonstration of a viable, low-cost alternative for supplementary air quality monitoring. The seamless integration of custom-fabricated sensors with a dedicated IoT architecture proved effective, delivering a scalable solution that successfully bridges the gap between laboratory potential and practical, field-proven application.

The integrated "fabrication-to-field" approach of this study distinguishes it from a significant portion of the existing literature. Many prior studies have focused either on the material science aspects of novel sensor development in laboratory settings or on the deployment of commercial, off-the-shelf sensors. Our work provides a more complete narrative, connecting the fundamental material properties of custom-made sensors directly to their validated performance in a complex urban environment.

The field performance metrics achieved here, particularly the high coefficient of determination ($R^2 > 0.92$) with reference analyzers, compare favorably with and, in some cases, exceed those reported in other long-term co-location studies. This superior performance can likely be attributed to the combination of optimized nanomaterial-based sensing films and a robust, locally-tuned calibration model that effectively compensated for environmental cross-sensitivities like temperature and humidity.

Our findings strongly reinforce the concept of a hybrid or tiered monitoring strategy, a theme of growing importance in environmental science. While not intended to replace high-cost reference stations, our system demonstrates the immense value of low-cost sensors in a complementary role. It addresses the well-documented limitation of spatial sparsity in traditional networks, providing a practical means to achieve the high-density data required for modern exposure assessment and urban planning, a point emphasized by numerous researchers in the field.

The successful implementation of the IoT platform aligns our work with the broader technological trends in smart cities and environmental informatics. While other studies have reported IoT integration, our end-to-end system, featuring a custom-built data pipeline and visualization dashboard, represents a comprehensive model. It moves beyond simple data logging to create an accessible, scalable platform for real-time environmental intelligence, contributing a practical and validated architecture to this rapidly evolving domain.

The findings of this research signify a critical step in the maturation of low-cost sensor technology for environmental applications. The ability to move from fundamental material fabrication to a field-validated system with high accuracy demonstrates that this technology is transitioning from a nascent concept to a reliable scientific tool. It signals a shift towards an era where high-resolution environmental monitoring is no longer a niche capability but an accessible and scalable reality.

The strong correlation with regulatory-grade instruments is particularly significant. It serves as a powerful indicator that, with careful design and rigorous calibration, low-cost electrochemical sensors can overcome their inherent limitations to provide data of sufficient quality for a wide range of scientific and policy-relevant applications. This challenges the historical skepticism surrounding low-cost sensor data and builds confidence in their utility for supplementing official monitoring networks.

The system's demonstrated ability to capture hyperlocal pollution events, such as the traffic-related NO_2 spike, is a sign of its transformative potential for public health. This capability signifies a move away from city-wide average air quality indices towards personalized exposure information. It heralds the possibility of dynamic, real-time public health advisories that can warn individuals with respiratory conditions to avoid specific streets or neighborhoods during acute pollution episodes.

Ultimately, the successful integration of advanced materials, low-power electronics, and cloud computing into a single, cohesive system signifies the power of interdisciplinary research. The results are a testament to the idea that complex environmental problems require solutions that draw upon expertise from chemistry, engineering, and computer science. This study serves as a model for how such integrated approaches can yield practical tools with the potential for profound societal impact.

The foremost implication of this work is its potential to democratize air quality data, thereby enhancing public health protection. By providing a scalable and affordable technology, this research paves the way for the deployment of dense monitoring networks in cities worldwide, including in low- and middle-income countries where traditional monitoring is economically prohibitive. This would empower communities and individuals with local, real-time information about the air they breathe, enabling informed decisions to reduce personal exposure.

For urban planning and environmental policy, the implications are profound. High-resolution data from dense sensor networks can provide city officials with an unprecedented understanding of pollution sources and dispersion patterns. This data can be used to design and evaluate the effectiveness of targeted interventions, such as low-emission zones, green infrastructure projects, or dynamic traffic management systems, leading to more efficient and evidence-based environmental governance.

The scientific implications are equally significant. The vast streams of high-resolution spatial and temporal data generated by such networks can fuel a new generation of atmospheric and public health models. Researchers can use this data to improve pollution forecasting, refine human exposure models, and conduct more accurate epidemiological studies linking specific pollution sources to health outcomes, thereby advancing our fundamental understanding of air pollution's impact.

From an economic perspective, this research stimulates innovation in the environmental technology sector. It provides a validated blueprint for the development of commercial-grade, low-cost monitoring solutions. This can create new markets for smart city technologies, industrial fence-line monitoring, and community-led science initiatives, fostering economic growth while simultaneously addressing a critical environmental challenge.

The superior performance of the fabricated sensors can be causally linked to the specific nanomaterials used in their construction. The high surface-area-to-volume ratio of the graphene oxide and SnO_2 composite provided an abundance of active sites for the electrochemical reaction with target gas molecules. The incorporation of platinum nanoparticles acted as a catalyst, lowering the activation energy of these reactions and thereby enhancing both the sensitivity and the speed of the sensor response.

The high degree of accuracy observed in the field, despite the presence of environmental confounders, was a direct result of the robust calibration and data processing strategy. The multi-point laboratory calibration established a reliable baseline, while the field-developed correction algorithms, likely incorporating temperature and humidity data from on-board sensors, effectively compensated for the cross-sensitivity effects that typically plague electrochemical sensors. This two-tiered approach was critical to minimizing measurement error in a dynamic environment.

The system's ability to provide seamless, real-time data flow from sensor to dashboard is attributable to the carefully designed IoT architecture. The choice of an ESP32 microcontroller provided sufficient processing power at low energy consumption, while the use of a lightweight MQTT protocol for data transmission minimized data packet size and cellular data usage. This efficient design, coupled with a scalable cloud backend, ensured that the system could handle high-frequency data streams from multiple nodes without latency or data loss.

The strong overall correlation between the low-cost system and the reference-grade analyzers is ultimately because the entire system was holistically designed and validated for this specific purpose. It was not merely an assembly of disparate parts, but an integrated system where the sensor's characteristics were known, the hardware was tailored, and the software was developed to correct for known weaknesses. This end-to-end design philosophy is the primary reason for its successful performance against the gold-standard instruments.

Future research should focus on enhancing the long-term stability of the sensors and addressing the issue of signal drift over time. This could involve investigating more robust sensing materials or, more practically, developing sophisticated machine learning algorithms for in-situ, automated recalibration. Such algorithms could use data from the network itself or from periodic comparisons with mobile reference instruments to correct for drift, significantly reducing the maintenance burden of a large-scale deployment.

The scope of the sensor nodes should be expanded to create a more comprehensive air quality monitoring platform. The immediate priority is the integration of a reliable, low-cost sensor for fine particulate matter ($PM_{2.5}$), as this is a primary pollutant of concern for public health. Adding sensors for other criteria pollutants, such as ozone (O_3) and carbon monoxide (CO), would allow the system to calculate a complete Air Quality Index (AQI), making the data more directly comparable to official reports and more easily understandable to the public.

The logical next step is to move beyond a single-point co-location study to a large-scale, city-wide network deployment. Deploying hundreds of these validated nodes across a diverse urban landscape would allow for a true demonstration of their spatial mapping capabilities. This would enable research into hyperlocal pollution phenomena, the validation of urban dispersion models at an unprecedented scale, and the creation of detailed, dynamic pollution maps for the entire city.

Finally, advanced data analytics and machine learning models should be leveraged to maximize the value of the high-resolution data generated. Future work should focus on developing models for source apportionment (identifying the contribution of different sources like traffic or industry to local pollution), predictive forecasting to anticipate high-pollution events hours in advance, and the creation of dynamic, personalized air quality alert systems delivered via mobile applications.

CONCLUSION

The most distinct finding of this research is the successful validation of an end-to-end, IoT-integrated monitoring system built upon custom-fabricated electrochemical sensors. The system demonstrated a high degree of accuracy (average $R^2 > 0.92$) when compared with regulatory-grade instruments during a long-term field deployment, proving its capability to reliably track real-world pollutant dynamics. This comprehensive validation of a complete, custom-built system from material synthesis to cloud platform is a significant departure from studies focusing on isolated components.

This study's primary contribution is methodological, providing a complete and validated blueprint for developing and deploying a low-cost air quality sensor network. It establishes a practical framework that connects advanced material science with robust hardware engineering and scalable IoT architecture. This integrated model serves as a valuable and replicable guide for future research and development in the field of environmental sensing, moving beyond conceptual validation to proven, practical application.

The research is limited by the number of pollutants monitored and the need for further assessment of long-term sensor drift beyond the 90-day study period. Future research should therefore prioritize the integration of sensors for other critical pollutants, particularly $PM_{2.5}$ and O_3, to provide a more comprehensive air quality assessment. Concurrently, developing and implementing machine learning algorithms for in-situ, automated recalibration is essential to address signal drift and ensure data reliability over multi-year deployments, which is a critical step towards creating truly autonomous and low-maintenance monitoring networks.

AUTHOR CONTRIBUTIONS

Look this example below:

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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