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Development of an Integrated Air Quality Monitoring System for Temperature, Humidity, CO, and PM10 Measurement

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ABSTRACT

This study addresses the growing need for cost-effective and straightforward air quality monitoring solutions. We present the development and testing of an integrated sensor system combining DHT11, MQ-7, and GP2Y1010AU0F sensors for measuring temperature, humidity, CO gas, and PM10 levels. Our calibration tests demonstrate a sensor accuracy exceeding 96%, with individual accuracy rates for temperature, humidity, CO, and PM10 sensors at 98.42%, 96.81%, 96.95%, and 97.75%, respectively. These findings underscore the potential of our integrated sensor design in providing reliable and affordable air quality monitoring for community use.

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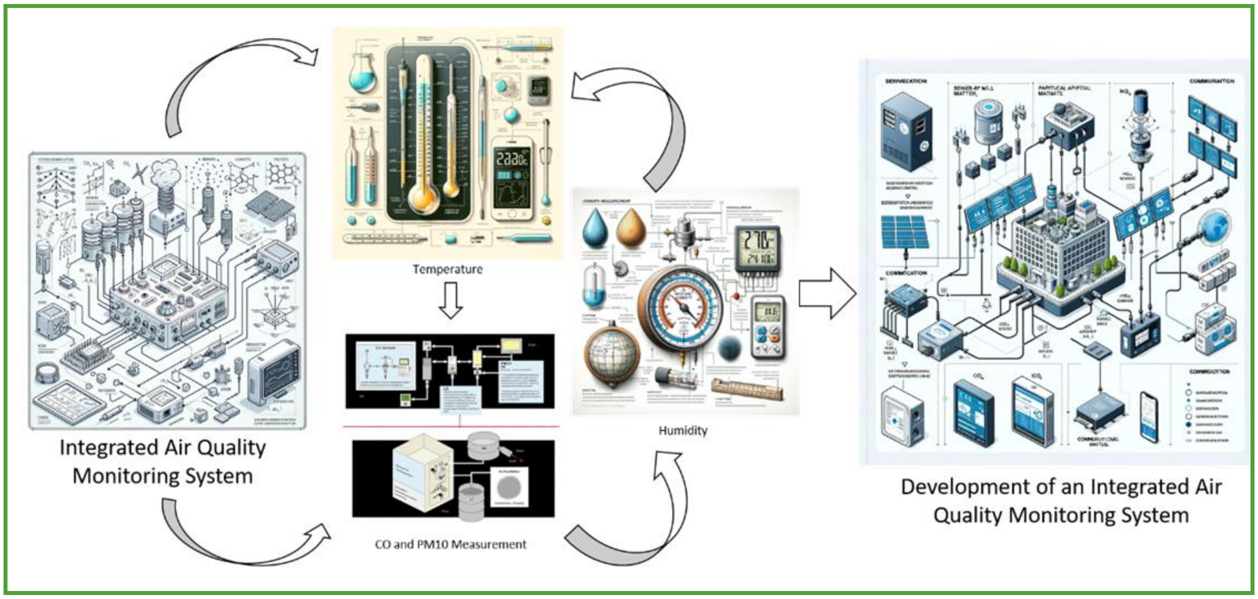
Graphical Abstract



Introduction

The issue of air pollution today is escalating to a critically alarming state. Air pollution originates from a multitude of activities, encompassing industrial operations, transportation, office buildings, and residential areas [1, 2]. These activities constitute the primary sources of air pollutants released into the atmosphere. Moreover, various natural phenomena, including forest fires, volcanic eruptions, and the release of toxic gases, also significantly contribute to air pollution [3]. Such pollution adversely affects air quality, thereby negatively impacting human health [4-7].

This challenge has escalated into a global environmental concern. A World Health Organization (WHO) survey in 2002, covering 1,600 cities across 91 countries, revealed that nearly 90% of urban inhabitants are exposed to air quality levels deemed unhealthy [8]. The WHO further reported that approximately half of the global population is exposed to pollution levels at least 2.5 times higher than the recommended air quality standards. This issue is particularly pronounced in developing countries, such as Indonesia, where rapid development driven by economic growth exacerbates pollution [9-11].

Respiratory health issues represent a significant societal burden. The WHO, in 2000, reported that respiratory diseases rank among the top five illnesses contributing to mortality, accounting for 17.4% of all deaths and 13.3% of all disability-adjusted life years (DALYs) [12]. Diseases such as lower respiratory infections [13-15], chronic obstructive pulmonary disease (COPD), tuberculosis, and lung cancer are among the leading causes of death globally [16-18].

It is a well-acknowledged fact that urban residents spend a substantial portion of their time indoors. This demographic predominantly includes children, infants, the elderly, office employees, and individuals with chronic conditions. The concentration of pollutants in indoor environments, such as homes, workplaces, and public buildings, can significantly differ from outdoor pollution levels. Indoor air quality deteriorates not only due to the infiltration of external pollutants, but also from internal sources like cigarette smoke, cooking emissions, and the use of insect repellents. The importance of indoor air quality cannot be overstated, given its profound impact on respiratory health [19, 20]. The National Institute of Occupational Safety and Health (NIOSH) attributes indoor air quality issues to several factors, including inadequate ventilation (52%), indoor contaminant sources (16%), external pollutants (10%), microbial agents (5%), and building materials (4%), among others (3%) [21].

Various countries have adopted distinct indices to gauge ambient air quality, such as the Air Quality Index (AQI) in the United States and the Air Pollution Standard Index (ISPU) in Indonesia [22]. Air quality is a critical factor for human survival [23-26]. However, urban development and industrial expansion have led to deteriorating air quality, a pressing concern in urban areas [27-29]. In Indonesia, urban air quality has been on a decline over the past decade, with economic growth and urbanization being key contributors to this trend [30-32].

The demand for transportation and energy escalates with population growth, urban development, and lifestyle changes due to increased income levels. This surge in energy consumption further exacerbates air pollution, culminating in economic losses and elevated healthcare costs [33-36].

In response to these challenges, various air quality detection technologies continue to evolve [37]. Nevertheless, there is a pressing need for innovation in sensor system designs, considering the limitations and operational challenges associated with current market offerings. This scenario presents an opportunity for researchers to develop simpler, more user-friendly, and cost-effective sensor designs. In this context, the integration of the DHT 11 sensor, GP2Y1010AU0F dust sensor, and MQ-7 sensor module represents a novel approach in the ongoing effort to monitor air quality.

The advent of sophisticated air quality monitoring technologies over the past decade has significantly enhanced our capability to detect and analyze atmospheric pollutants. These technologies have evolved rapidly, driven by advancements in sensor accuracy, data processing algorithms, and the integration of Internet of Things (IoT) frameworks. Several studies and reviews highlighted the progress and challenges in this domain, offering insights into the state-of-the-art monitoring techniques and their implications for environmental health and policy [38].

Low-cost sensor networks have gained prominence for their potential to democratize air quality monitoring. These sensors, which can measure pollutants such as PM2.5, NO_2, and O_3, have been increasingly deployed in dense networks across urban areas. Despite their lower accuracy compared to regulatory-grade instruments, their affordability and flexibility allow for high-resolution spatial and temporal pollution mapping [38]. However, ensuring data quality and sensor calibration remains a challenge.

Satellite Remote Sensing technologies have also advanced, providing comprehensive global coverage of air pollutants. The TROPOspheric Monitoring Instrument (TROPOMI) on the Sentinel-5 Precursor satellite, for example, offers unprecedented spatial resolution for monitoring nitrogen dioxide (NO_2) and other gases. These satellite datasets, when combined with ground-based observations, enhance our understanding of pollution sources and transport mechanisms on a global scale [39].

IoT-based monitoring systems represent another leap forward, integrating sensors with cloud computing and data analytics to offer real-time air quality monitoring and forecasting. These systems leverage the power of machine learning algorithms to predict air quality indices, enabling proactive management of pollution events. The scalability of IoT frameworks facilitates the deployment of multisensory networks that can monitor a wide array of environmental parameters beyond traditional pollutants, including temperature, humidity, and airborne particulates [40].

Emerging technologies and big data analytics are transforming air quality monitoring into a more dynamic and interactive field. Developments in artificial intelligence (AI) and machine learning (ML) are particularly noteworthy, as they improve the predictive capabilities of monitoring systems, enabling them to forecast pollution levels with greater accuracy. Big data analytics also play a crucial role in assimilating data from diverse sources, providing a holistic view of air quality and its health impacts [41].

In light of these advancements, the proposed system seeks to integrate the strengths of these diverse technologies to offer a comprehensive and accessible air quality monitoring solution. By combining the real-time data collection capabilities of IoT-based sensors with the analytical power of AI and big data, the system aims to provide accurate, actionable air quality information to communities and policymakers alike.

Experimental

In the design process of our tool, we utilized various interconnected hardware components, which were programmed in accordance with the flowchart presented in Figure 1, ensuring the system operates as intended.

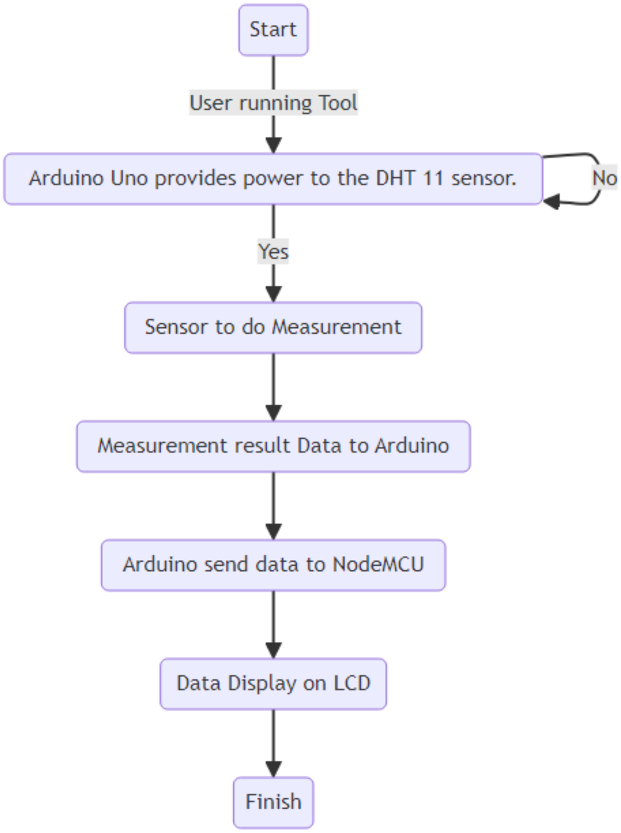


Figure 1. Flowchart design for device software

The primary hardware includes an Arduino Uno, which facilitates the process of reading data from the DHT 11 sensor, the MQ-7 sensor, and the GP2Y1010AU0F dust sensor, thereby assessing the indoor air quality. Digital data transmission to an LCD screen is executed using a NodeMCU ESP8266. The comprehensive design, encompassing both hardware and software components, is depicted in Figure 2.

The components illustrated in Figure 2 are detailed as follows: The Arduino Uno serves as the core controller, powering, and issuing commands to each sensor for air quality measurement within a room and forwarding sensor data to the NodeMCU ESP8266 via TX-RX pin connections. The DHT 11 sensor is employed for recording room temperature and humidity. Carbon Monoxide (CO) gas levels are measured using the MQ-7 sensor. To quantify Fine Particles measuring +10 microns (PM10) in the room, a GP2Y1010AU0F dust sensor, along with a 150Ω resistor and a 220μF capacitor, is utilized. Measurement data from each sensor are displayed on a 16 x 4 LCD, interfaced through an I2C module.

For our data collection methodology, sensor accuracy was verified by juxtaposing the sensor data with that from standard, commercially available instruments. This involved calculating the mean measurement results, standard deviation, percentage error (absolute percentage error), mean absolute percentage error (MAPE), and sensor accuracy levels. The accuracy testing for each sensor involved the use of distinct commercial tools corresponding to the measured parameters, as outlined in Table 1.

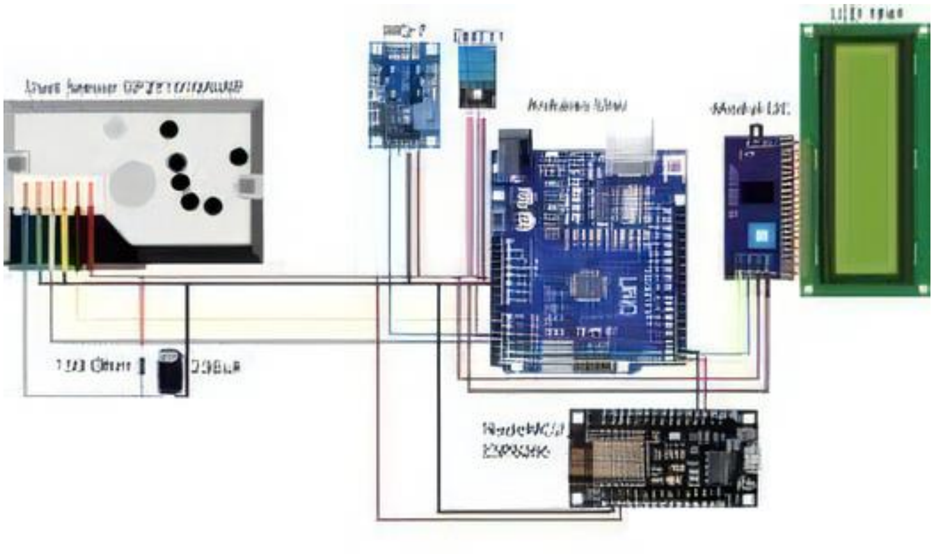


Figure 2. The overall circuit for device hardware

Table 1. Commercial tools used for comparison

No.	Type of parameter	Unit	Commercial tool used
1	Temperature	°C	Hygrometer HTC-1
2	Humidity	%	Hygrometer HTC-1
3	Fine Particles (PM10)	$\mu g/m^3$	Air Quality Detector TFT
4	CO Gas	ppm	Kerui CO Detector

In the calibration process of our air quality monitoring system, we adopted a meticulous approach to ensure the accuracy and reliability of our sensor readings, drawing upon recent advancements and best practices in the field. The calibration involved comparing our system's sensor readings against those from selected commercial equipment known for their precision and reliability in measuring air pollutants.

Rationale for equipment selection

The selection of commercial equipment for comparison was based on their established accuracy, reliability, and widespread use in the scientific community for air quality monitoring. These instruments have been validated in various environmental conditions, offering a robust benchmark for calibrating our sensors. Recent studies have emphasized the importance of selecting well-established reference instruments for sensor calibration to ensure the quality and reliability of data collected by low-cost sensors [42].

Calibration process

We employed a spatial calibration model, as recent research suggests that spatial calibration can significantly improve the accuracy of sensor data by accounting for spatially varying relationships between sensor readings and actual pollutant concentrations. This approach allows for the correction of biases and enhancement of data reliability across different locations, making it possible to estimate air quality levels with greater precision [43]. Furthermore, the methodology emphasizes the importance of considering environmental variables such as temperature and humidity, which can affect sensor performance, and recommends quantile mapping as an effective calibration technique for mobile measurements, retaining the spatial characteristics of the measurements and ensuring data accuracy across different conditions [44].

By integrating these advanced calibration techniques and carefully selecting reference equipment, we aimed to enhance the accuracy and reliability of our air quality monitoring system. This detailed calibration process, grounded in the latest research and best practices, ensures that our system can provide valuable and trustworthy data for air quality assessment.

Results and Discussion

Sensor design

The sensor device was designed with compact dimensions of 10x10x12 cm, enabling it to effectively assess and provide air quality recommendations for indoor environments, as depicted in Figure 3.

Sensor calibration

Calibration tests for the sensors were conducted alongside standard sensors to ensure accuracy. Measurements were taken repeatedly at a 10 cm distance from the test object. The calibration results demonstrated high accuracy levels across the sensors: temperature, CO, and PM10 sensors achieved accuracy rates of 99.37%, 96.83%, and 97.77%, respectively.

Sensor test results

The DHT 11 sensor was compared against a standard HCT 1 Hygrometer sensor across varying distances (5 cm to 25 cm) to test temperature measurement accuracy. The results, illustrated in Figure 4, show a high degree of alignment between the two sensor outputs, confirming a sensor accuracy of 98.42% for temperature measurements.

Figure 3. Sensor circuit: (a) outside view and (b) inside view

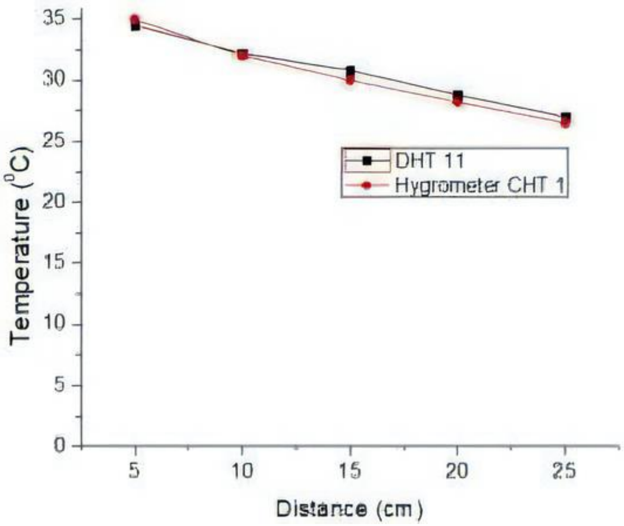


Figure 4. Temperature test results plot graph

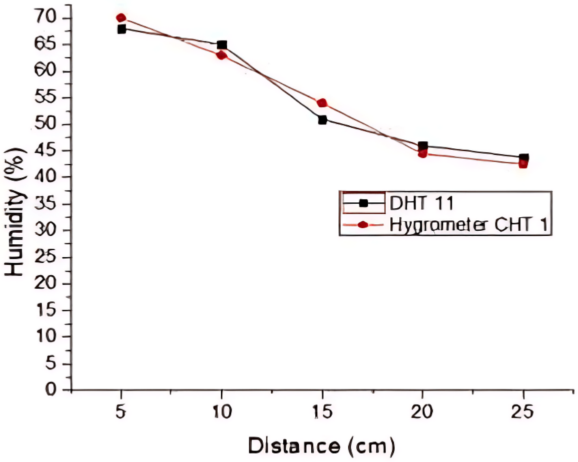


Figure 5. Humidity test results plot graph

Humidity measurements, shown in Figure 5, further corroborate the sensor's reliability, with a nearly identical trend observed between the DHT 11 sensor and the standard sensor, yielding an accuracy of 96.81%.

CO gas testing involved comparing the MQ-7 sensor with a Kerui detector, using vehicle exhaust as the CO source at a 15 cm distance. Figure 6 presents the test results, where the MQ-7 sensor readings closely match those of the Kerui detector, indicating a sensor accuracy of 96.95%.

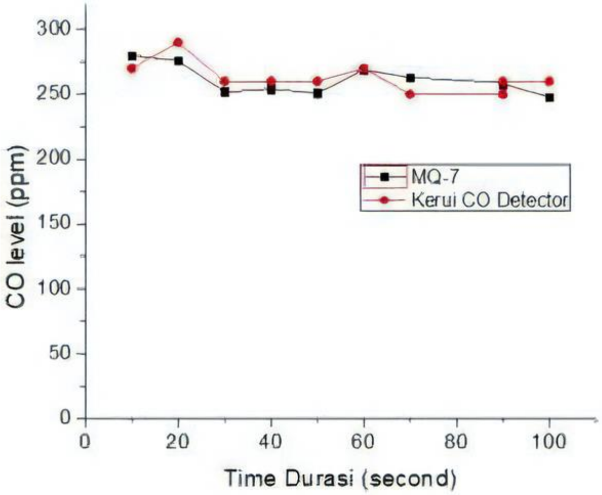


Figure 6. CO levels measurement plot graph

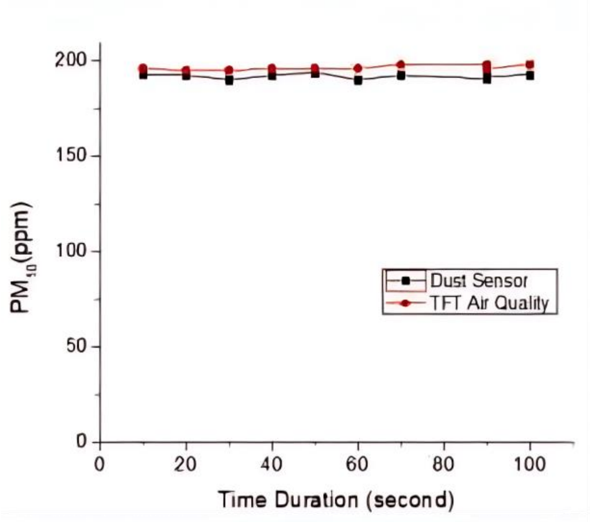


Figure 7. PM10 level test results plot graph

The GP2Y1010AU0F dust sensor's ability to detect PM10 levels was evaluated by exposing it to cigarette smoke alongside a TFT Air Quality tool. The comparative results, depicted in Figure 7, show a consistent reading between both sensors, affirming a sensor accuracy of 97.75%.

The paper presents a comprehensive development and testing of an integrated air quality monitoring system, showcasing a significant advancement in sensor technology for environmental health. By achieving over 96% accuracy in measuring temperature, humidity, CO gas, and PM10 levels, the study underlines the potential for deploying cost-effective and reliable air quality monitoring tools in community settings. This high level of accuracy demonstrates the effectiveness of the integrated sensor design, which combines DHT11, MQ-7, and GP2Y1010AU0F sensors, for precise air quality assessment.

This study addresses the urgent global need for accessible air quality monitoring solutions, especially in light of WHO reports highlighting widespread exposure to unhealthy air quality levels. The integration of the sensors with a microcontroller reflects a promising approach towards creating user-friendly devices capable of providing accurate environmental data, which is crucial for public health initiatives and policy-making. This development is particularly relevant for rapidly urbanizing regions where traditional monitoring infrastructure may be lacking or insufficient.

The study's findings advocate for the broader adoption of integrated sensor systems as a viable solution to the air quality monitoring challenges posed by urbanization and industrial activity. By offering a detailed analysis of sensor accuracy and calibration methods, the paper contributes valuable insights to the field of environmental monitoring technology. It paves the way for further research into scalable, affordable air quality monitoring systems that could significantly impact public health and environmental policy.

The study marks a pivotal advancement in air quality monitoring, showcasing precise measurement capabilities across vital environmental factors. The integrated sensor system's high accuracy in gauging temperature, humidity, CO, and PM10 positions it as a dependable tool for indoor air quality assessment, pivotal for health. Its precision highlights its potential to bridge existing gaps in monitoring practices, providing an affordable and community-friendly solution.

Enhanced by rigorous calibration and testing, the study accentuates the sensor system's consistency and reliability in data production. Its alignment with standard tools under varied conditions confirms its trustworthiness for precise environmental surveillance, making it instrumental in early pollution detection and health risk management.

These insights herald a shift towards proactive public health strategies and policy development. The system's real-time air quality monitoring capability informs better pollution control and health advisory decisions. Advocating for its widespread adoption, the study suggests a scalable approach that could revolutionize air quality monitoring, aiming to mitigate air pollution's health impacts globally.

Recent advances in air quality monitoring technology underscore the integration of Internet of Things (IoT) devices, advanced sensor arrays, and machine learning algorithms to deliver real-time, precise, and comprehensive data on a broad spectrum of pollutants [45-47]. This movement towards Smart Environment Monitoring (SEM) systems, which employ networks of interconnected sensors, aims to scrutinize air quality, water purity, radiation levels, and agricultural health comprehensively [48-50]. These systems are designed to furnish actionable insights for both governmental bodies and the general populace, facilitating swift actions in the face of environmental hazards and contamination.

This study contributes significantly to this domain by unveiling an integrated air quality monitoring system that specifically targets temperature, humidity, carbon monoxide (CO) gas, and PM10 particulate levels. By employing specialized sensors- DHT11 for temperature and humidity, MQ-7 for CO gas, and GP2Y1010AU0F for PM10 levels- and achieving high accuracy, this study stands out as a crucial tool for community-level environmental surveillance. Notably, its focus on cost-effectiveness and precision mirrors the global drive towards developing accessible and dependable environmental monitoring solutions.

On a broader scale, research is pivoting towards more holistic and advanced systems that harness the power of IoT and machine learning not just for gathering data but also for predictive analytics, automatic response frameworks, and integration into comprehensive city or region-wide environmental management systems. These avant-garde systems aspire to encompass a more extensive array of contaminants, including fine particulate matter (PM2.5), nitrogen oxides (NOx), and volatile organic compounds (VOCs), and are tailored to operate across varied settings, from bustling urban landscapes to secluded locales. This paper lays foundational groundwork within this rapidly evolving sector, underscoring the critical role of focused, high-precision monitoring solutions that are scalable and integrable into broader smart city strategies.

In essence, while the specific concentration and technological methodology of this study mark a pivotal advancement towards efficacious air quality monitoring, the arena is swiftly transitioning towards more interconnected, intelligent, and all-encompassing monitoring solutions. These innovative solutions aim not only to amass data, but also to interpret and utilize this information in ways that markedly enhance our mitigation strategies against environmental adversities.

Analysis of potential errors and limitations of sensor systems, including the impact of environmental factors on sensor performance and measures to mitigate such impacts, the following points can be integrated based on the latest findings:

Environmental and sensor limitations

Research has highlighted that environmental factors such as the inherent optical properties of water, bathymetry, sun height, wind speed, and sensor noise characteristics can significantly impact sensor performance. A model developed to analyze these impacts shows that benthic-type spectral variations and sub-pixel mixing are the main limiting factors for mapping purposes, while instrument noise levels are relatively small [51].

Wireless sensor network (WSN) challenges

In the context of IoT applications, WSNs face challenges related to communication security, data bias due to environmental conditions such as high humidity, and the need for accurate calibration methodologies to ensure data reliability. New approaches involving true random number generators based on ADC nonlinear effects and chaos maps have been proposed to address some of these challenges, emphasizing the importance of robust calibration and data security protocols [52].

Mitigation strategies

To mitigate the impact of environmental factors on sensor performance, several strategies can be implemented. This includes using spatial calibration models to correct bias and increase data reliability at multiple locations, adjusting calibration methodology based on environmental conditions, and incorporating quantile mapping for mobile measurements to maintain the spatial characteristics of measurements.

The need for further validation of air quality sensors in diverse environmental conditions to strengthen findings has been addressed in several recent studies. For example, a study described in [53] highlighted the deployment of AirSensEUR sensor systems across multiple cities, capturing a broad range of meteorological conditions and pollutant concentrations. This study emphasized the importance of evaluating sensor performance across different traffic impacts and spatial variability within urban environments, which is critical for assessing sensor accuracy and reliability in real-world conditions [53].

Another study published in [54] focused on field tests and validation of particulate matter measurements using low-cost sensor nodes. The study involved mounting sensor-boxes on utility vehicles for mobile air quality monitoring in Central Switzerland, comparing the data collected to a regional air quality monitoring network. This approach allowed for the assessment of sensor performance in varying environmental conditions, including different levels of pollutants and meteorological influences. The study also delved into data filtering methods to enhance the quality of the sensor data, showing the potential for low-cost sensors to deliver coherent data across a region [54].

These studies underscore the importance of validating air quality sensors in diverse environmental settings to ensure the accuracy and reliability of the data they produce. By conducting extensive field tests and comparing sensor data to established reference data, researchers can identify and correct for factors that may affect sensor performance, such as environmental conditions and sensor drift. This process is crucial for the effective use of low-cost sensors in air quality monitoring, especially in urban areas where pollutant concentrations and environmental conditions can vary significantly.

Regarding the long-term stability and maintenance requirements of the air quality sensor system. The first study, as detailed in [55], focuses on the calibration process of low-cost particle sensors for indoor air pollution health studies. It involved repeated calibration in a controlled environment using cigarette smoke and HEPA-filtered air to develop calibration curves for Airbeam sensors. This rigorous calibration process, conducted over a two-year period, underscores the necessity of periodic recalibration to maintain sensor accuracy over time. The study also highlighted the potential challenges in maintaining sensor performance, including equipment failures due to environmental conditions like humidity and temperature extremes, as well as other factors such as insect infestations [55].

Another important study published in [56] examines the performance of low-cost air quality sensors over a 13-month period in diverse environments in Australia and China. This study evaluated parameters such as inter-variability, accuracy, and the effect of environmental conditions on sensor performance. It found that while the sensors showed good long-term stability and high correlation in measurements of PM2.5 and CO, their accuracy and performance could be affected by extreme temperatures and relative humidity levels. In addition, the sensors' sensitivity varied across different types of aerosols, highlighting the importance of considering the specific environmental conditions and aerosol compositions when deploying these sensors for long-term monitoring [56].

Incorporating considerations of user interface and experience for deploying air quality sensors in community settings could indeed enhance the impact and usability of such technologies. Two studies provide insights into this area, emphasizing the need for intuitive, accessible platforms for data analysis and visualization, as well as thoughtful deployment strategies that address local contexts and resource constraints.

The first study, published in [57], outlines the development of an open-source framework for citizen-centric environmental monitoring and data analysis. This framework includes the Soc-IoT and exploreR, tools designed to reduce technical barriers and facilitate data analysis and visualization by both experts and non-experts. The exploreR application, developed using the RShiny package, offers an intuitive GUI that guides users through the data analysis process, from input and preprocessing to advanced analysis and forecasting. This approach underscores the importance of creating user-friendly interfaces that can engage diverse community members in environmental monitoring efforts [57].

The second study, featured in [58], focuses on design considerations for a distributed low-cost air quality sensing system tailored for urban environments in low-resource settings. This study highlights the AirQo system, a custom environmental sensing and management system designed for African cities. The AirQo platform provides tools for calibration, data access, and analytics, supporting usage among policymakers and citizens. Case studies from African cities using the system for education, awareness, and policy highlight the system's role in filling data gaps in urban air quality monitoring. This study emphasizes the importance of considering local infrastructure, environmental conditions, and the needs of communities when deploying technology-driven solutions in low-resource settings [58].

These studies collectively illustrate the crucial role of user interface and experience in the successful deployment of air quality sensors in community settings. By focusing on the ease of use, accessibility, and local context, environmental monitoring technologies can better serve and engage communities, leading to more effective and sustainable solutions for addressing air quality issues.

Conclusion

The development of a sensor system incorporating DHT11, MQ-7, and GP2Y1010AU0F sensors, controlled by a microcontroller, has successfully demonstrated high accuracy in monitoring temperature, humidity, CO, and PM10, with rates of 98.42%, 96.81%, 96.95%, and 97.75% respectively. This underlines the system's reliability in air quality assessment. Future research should explore integrating IoT for real-time data transmission and machine learning algorithms for predictive analytics, enhancing decision-making capabilities in environmental monitoring. This integration could offer adaptive responses to changing air quality conditions, optimizing monitoring strategies.

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Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the article and agreed to be responsible for all the aspects of this work.

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