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Low Cost Sensor Technology Innovation in Air Quality Monitoring: A Systematic Literature Review on Opportunities for Public Budget Efficiency

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A B S T R A C T

Air quality monitoring is critical in supporting environmental and public health policies, but conventional station-based methods still have limitations in cost and area coverage. Alternatively, low-cost sensor technologies based on the Internet of Things (IoT) and Artificial Intelligence (AI) offer solutions that are more economical, flexible, and capable of real-time monitoring. However, low-cost sensors face the challenge of lower accuracy compared to conventional sensors and require regular calibration for reliable measurement results. This paper analyzes the development of low-cost sensor technology, its effectiveness compared to conventional technology, and its impact on public budget efficiency. The results show that the integration of AI and IoT can improve the accuracy of low-cost sensors, while the citizen science model has the potential to expand monitoring coverage by involving the public in data collection. With the right strategy, low-cost sensors can be an inclusive and sustainable solution to support more cost-effective and data-driven environmental policies.

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1. INTRODUCTION

Air quality plays an important role in maintaining human health and environmental balance. According to the World Health Organization (WHO), air pollution causes around 7 million premature deaths annually due to respiratory and cardiovascular diseases triggered by exposure to pollutants such as PM2.5, NO_2, and CO_2 [1]. Therefore, air quality monitoring is a crucial step in supporting environmental and public health policies.

Currently, air quality monitoring is generally conducted through fixed monitoring stations that use advanced sensor technology with a high level of accuracy. However, this method has a major obstacle, namely large procurement and operational costs. Research conducted revealed that the construction of one conventional air quality monitoring station can cost very high, not including the cost of maintenance and operation [2]. This poses a challenge for the government, especially in regions that have limited budgets.

As an alternative solution, low-cost sensor innovations for air quality monitoring are being developed. These technologies are based on the Internet of Things (IoT) and artificial intelligence (AI), enabling real-time air quality monitoring with wider coverage and lower costs . Although these sensors have limitations in terms of accuracy compared to conventional sensors, it showed that the application of AI-based calibration and data processing technologies can significantly improve sensor reliability. In addition to its technological benefits, the use of low-cost sensors also has great potential in reducing the public budget allocated to air quality monitoring systems. A study shows that with lower costs, these sensors can be installed in greater numbers so that the monitoring coverage becomes wider and more representative than conventional systems [3]. Thus, the use of low-cost sensors can be a strategic step for the government in managing public budgets more efficiently.

Given the challenges in air quality monitoring and the potential solutions offered by low-cost sensor technology, this research focuses on analyzing the development of such innovation and its impact on public budget efficiency. Understanding how these technologies can be effectively implemented is essential to ensure that environmental policies remain both scientifically robust and economically feasible, especially in developing regions[4]. By conducting a literature review, this research is expected to provide an overview of the effectiveness, constraints, and optimal strategies in implementing low-cost sensors to support more cost-effective and sustainable environmental policies.

2. RESEARCH METHOD

This research uses a **Systematic Literature Review (SLR)** to analyze the development of low-cost air sensors (LCAS), their accuracy compared to conventional technologies, and their potential to improve public budget efficiency.

The review was conducted in three main steps:

1. **Planning**
   Research questions were formulated to explore LCAS trends, performance, and fiscal implications. Inclusion criteria focused on peer-reviewed studies from 2013–2024 related to outdoor air quality monitoring.
2. **Data Collection**
   Literature was sourced from **Google Scholar**, **ScienceDirect**, and **SpringerLink** using keywords such as *"low-cost air sensors," "air quality monitoring," "IoT,"* and *"budget efficiency."* After screening for relevance and quality, selected papers were reviewed in full.
3. **Analysis**
   The selected studies were examined to identify discussions on sensor performance, calibration techniques, integration with IoT or AI, implementation strategies, and economic implications. Key themes and patterns were synthesized to reflect current developments, challenges, and opportunities, as discussed in sections 3.1–3.5.

This method offers a structured basis for understanding how LCAS technology can support more cost-effective and inclusive air quality monitoring systems.

3. RESULT AND DISCUSSION

3.1. Analysis of the Development of Low-Cost Sensor Technology for Air Quality Monitoring Based on Recent Literature Review

- Research on low-cost sensors for air quality monitoring continues to grow, especially in terms of accuracy, cost efficiency, and high-resolution pollutant detection.
- Research on low-cost sensors for air quality monitoring is growing, particularly in terms of accuracy, cost efficiency, and high-resolution pollutant detection .
- These sensors are widely used due to their broader data coverage and easier accessibility compared to conventional monitoring stations .
- Low-cost sensors are vulnerable to environmental factors such as temperature and humidity.
- Statistical and AI-based calibration methods can improve their accuracy by up to 80%.
- With only 5–10% of the cost of reference stations, low-cost sensors make it possible to conduct wider monitoring, including in highly polluted areas .
- Sensor networks offer more detailed data to support more targeted environmental policies.
- However, validation and standardization challenges remain to be addressed.
- Materials like graphene, metal oxide semiconductors (MOS), and conductive polymers enhance the sensitivity and selectivity of low-cost sensors.
- Graphene is efficient in detecting NO_2 and CO, while MOS is suitable for ozone and VOCs, although it lacks long-term stability.

- A major challenge is the lack of uniform regulatory standards and their sensitivity to extreme conditions.
- With advancements in auto-correction algorithms, nanotechnology, and AI, these sensors have the potential to become key components of a smarter and more efficient global air monitoring system.
- Integration with IoT and cloud technology enables real-time calibration, bringing these sensors closer to standard air monitoring systems [5-8].

3.2. Low-Cost Sensor Accuracy versus Conventional Technology

- The accuracy of low-cost sensors varies depending on the measured parameters and environmental conditions.
- Reported 93.55% accuracy for PM2.5 and 93.13% for PM10 using the ZH03B sensor.
- Recorded an accuracy of 94.28% using the k-NN method.
- Compared to more precise FRM and FEM technologies, low-cost sensors still face long-term accuracy limitations due to environmental and calibration factors.
- Developed an IoT-based system using DHT11 and MQ135 sensors to monitor temperature, humidity, and harmful gases via the Blynk Cloud platform.
- This implementation enables real-time data access, useful for environments with diverse pollution sources.
- Low-cost sensors can be installed in a wider range of locations with greater flexibility than conventional technologies.
- Data reliability still requires improvement through proper calibration and integration with advanced, model-based monitoring systems.
- Calibration is essential to ensure data consistency, as measurement results can be influenced by temperature, humidity, and other pollutants.
- Periodic data correction helps improve accuracy.
- Machine learning-based methods can reduce measurement deviations.
- Hybrid approaches comparing low-cost sensor data to reference systems can increase data reliability and validity.
- These sensors are effective for real-time monitoring, particularly in areas lacking formal monitoring infrastructure.
- For regulatory and research purposes requiring high accuracy, conventional technologies remain more reliable.
- Integrating low-cost sensors with advanced systems offers a strategic solution for broader data coverage at lower cost [9-13].

3.3. Key challenges in the implementation of low-cost sensors for air quality monitoring in various environments

- Low-cost sensors provide an economical solution for air quality monitoring.
- Their accuracy can be affected by environmental factors such as temperature, humidity, and dust contamination .
- Periodic calibration is necessary, as these sensors are prone to data drift over time .
- Calibration is difficult to perform in areas lacking access to a reference monitoring system [14,15].

3.4. The potential of low-cost sensor technology in reducing the public budget spent on air quality monitoring systems

- Low-cost sensors provide an economical solution for air quality monitoring.
- Low-cost sensors offer a more affordable air quality monitoring alternative compared to conventional technologies like FRM and FEM, which involve high installation, maintenance, and operational costs.

- Their compact size and low power consumption enable widespread deployment with a relatively small initial investment.
- Although they require periodic calibration, the use of IoT-based automation and machine learning can reduce the cost and frequency of manual calibration, increasing monitoring efficiency.
- This enables governments and environmental agencies to optimize budget allocations while maintaining broad and real-time monitoring coverage.
- The citizen science model allows the general public to participate in air quality monitoring by installing and managing sensors themselves.
- This model reduces reliance on government funding and enhances public awareness of air pollution issues.
- Several cities in Europe and the United States have successfully implemented this approach, yielding effective environmental data collection [16-18].

3.5. Strategies that can be implemented to improve the efficiency and utilization of low-cost sensors in support of environmental and public health policies

- The use of low-cost sensors (LCS) is an innovative approach in air quality monitoring, but accuracy remains a major challenge.
- Periodic calibration with reference sensors and AI-based correction models is essential to improve data reliability.
- Integration of LCS with Internet of Things (IoT) technology allows for real-time monitoring and more precise data analysis
- Major cities like Jakarta have adopted IoT-based systems to support environmental policy implementation.
- Public education and outreach on how to use and interpret LCS data are crucial.
- Collaboration among government, academia, and the private sector is needed to maximize the effectiveness of LCS in developing data-driven policies [19,20].

Table 1. Systematic Literature Review Table

No	Author (Year)	Research Objective	Method	Contribution
1	WHO (2021)	Establish global air quality guidelines for $PM_{2.5}$, PM_{10}, and other gases.	Literature review and global data analysis	Provided reference standards for healthier air quality.
2	Borrego et al. (2016)	Assess microsensor performance compared to reference methods.	Experimental comparative study	Microsensors show potential but require intensive calibration.
3	Budiman et al. (2023)	Implement wireless sensor networks (WSN) for environmental monitoring in Indonesia.	IoT-based WSN implementation	Efficient real-time air quality data collection.
4	Castell et al. (2017)	Evaluate low-cost sensors' contribution to pollution exposure monitoring.	Multi-city field study	Sensors useful for exposure estimation, but accuracy varies.
5	Harahap & Iskandar (2022)	Analyze sensor applications in environmental monitoring.	Descriptive study	Sensors proven effective for basic

No	Author (Year)	Research Objective	Method	Contribution
				monitoring applications.
6	Karagulian et al. (2019)	Review low-cost sensor performance.	Literature review	Affordable sensors valuable in specific contexts but limited by accuracy.
7	Kumar et al. (2015)	Discuss expanded use of low-cost sensors in cities.	Literature review	Low-cost sensors can support smart city policies.
8	Lewis et al. (2016)	Review applications, limitations, and calibration of low-cost sensors.	Scientific review	Provided technical guidelines for low-cost sensor use.
9	Lewis & Edwards (2018)	Validate personal air quality data.	Field experiments and validation	Individual data can complement official monitoring systems.
10	Mead et al. (2013)	Test electrochemical sensors in dense networks.	Field testing	Electrochemical sensors effectively detect urban pollutants.
11	Morawska et al. (2018)	Apply low-cost sensors for exposure monitoring and mapping.	Cross-country study	Sensors effective for epidemiological studies and exposure mapping.
12	Munir et al. (2019)	Analyze performance and calibration methods for low-cost sensors.	Technical and statistical evaluation	Sensor accuracy depends on calibration strategies.
13	Piedrahita et al. (2014)	Develop next-generation personal sensors.	Laboratory design and testing	Sensors enable real-time individual exposure data collection.
14	Snyder et al. (2013)	Explain paradigm shifts in pollution monitoring.	Technology trend analysis	New technologies enable more flexible monitoring.
15	Spinelle et al. (2017)	Field calibration of NO_2 and O_3 sensors.	Field testing and statistical analysis	Calibration enhances sensor data reliability.
16	Schneider et al. (2019)	Validate low-cost sensors in urban environments.	Field study	Sensors perform well in urban areas with supervision.
17	Sholahudin et al. (2024)	Evaluate low-cost sensor performance.	Laboratory performance testing	Sensors demonstrate stable performance under specific configurations.
18	Wang et al. (2015)	Laboratory evaluation of three particle sensors.	Laboratory testing	Sensors detect PM with moderate accuracy.

No	Author (Year)	Research Objective	Method	Contribution
19	Zheng et al. (2019)	Field-test sensors in environments with varying pollution levels.	Field study	Sensors perform better in high-pollution environments.
20	Arya et al. (2018)	Develop ML and WSN-based air pollution monitoring systems.	Prototype simulation and testing	Machine learning improves air quality prediction accuracy.

4. CONCLUSION

Low-cost sensors for air quality monitoring offer a cost-effective solution and wider coverage, although their accuracy is still limited. Improved accuracy can be achieved with AI and IoT-based calibration. Key challenges include calibration, sensitivity to extreme conditions, and lack of regulatory standards.

These sensors are effective for real-time monitoring, but require calibration and integration with analytics systems. The use of IoT and citizen science can reduce dependence on government budgets. With automatic calibration, low-cost sensors can reduce monitoring costs and support better environmental policies.

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