Grenze International Journal of Engineering and Technology, January Issue

Enhancing Home Air Quality: Solar-Powered IoT-based Purifiers for Indoor Environments

Chaitra Ganesh[1], Anitha H K[2], Nikitha M[3], Pooja Shivamurthy B[4] and Vishnu Theertha T[5]
[1]Assistant Professor, Department of EEE, Vidyavardhaka College of Engineering, Mysuru, Karnataka, India
Email: Chaitra.ganesh@vvce.ac.in
[2-5]Student, Department of EEE, Vidyavardhaka College of Engineering, Mysuru, Karnataka, India
Email: hkanitha5@gmail.com, nikithamnikitham27@gmail.com, poojashivamurthyb@gmail.com, vishnutheertha70@gmail.com

***Abstract*—Indoor air quality management makes use of engineering-standard sensor architectures, encompassing optical particle counters, electrochemical analysers, and semiconductor platforms for the detection of a wide range of pollutants. Wireless telemetry frameworks like WiFi, ZigBee, LoRaWAN, and GSM enable robust, low-latency data transmission and centralized control. Multi-stage purification modules, including HEPA filtration and catalytic substrates, ensure effective pollutant removal while renewable energy sources facilitate autonomous operation. System designs emphasise sensor calibration, data validation, and compliance with ISO/IEC/IEEE standards. Edge computing and supervisory dashboards optimise user oversight and support predictive maintenance. Performance metrics address detection fidelity, operational efficiency, spatial scalability, and cost optimisation, guiding large-scale deployments in urban, industrial, and remote settings. Engineering solutions focus on reliability, security, and adaptability for sustainable indoor air quality improvement.**

***Index Terms*— Indoor air quality, sensor arrays, particulate monitoring, wireless protocols, HEPA filtration, calibration, regulatory standards, renewable energy, scalability.**

I. INTRODUCTION

Indoor air quality has become a key public health issue, with the World Health Organisation estimating that about 3.8 million premature deaths each year are caused by household air pollution [1]. Dust is an unavoidable presence in homes, offices, and other indoor environments where people spend significant time [1]. According to the Environmental Protection Agency (EPA), indoor air is often two to five times more polluted than outdoor air [2]. This pollution can cause minor health issues such as headaches and eye irritation, and in more severe cases, it contributes to chronic allergies and debilitating respiratory conditions [3].
Pollution is a growing concern in the 21st century and is among the primary contributors to climate change. The COVID-19 pandemic has also increased focus on the maintenance of clean indoor environments, and there is a push towards accelerating R&D in smart air quality management systems [2]. Conventional methods for air purification and monitoring face a number of serious drawbacks, including high energy consumption, little adaptability, and the inability for real-time monitoring [3]. Against these risks, operational air-purification systems are increasingly integrated with smart sensors and microcontrollers.

Grenze ID: 01.GIJET.12.1.143_1

Unlike traditional systems that run continuously, intelligent systems detect the presence of pollutants and activate only when necessary. This sensor-based approach reduces power consumption and ensures consistently fresh indoor air.

The convergence of Internet of Things (IoT) technologies, wireless sensor networks (WSNs), and renewable energy systems has provided new avenues for designing intelligent, energy-efficient, and low-cost IAQ solutions [4]. Recent technological developments have made it possible to develop systems that can monitor several air quality parameters in real-time, adapt purification strategies based on pollutant concentrations, run autonomously by using renewable energy sources, and be integrated into smart home ecosystems for smooth operation.

II. METHODOLOGY

A. Wireless Telemetry

WiFi infrastructure is employed to facilitate high-throughput data transmission, interlinking sensor arrays with centralised supervisory control systems for near-real-time environmental analytics [10]. ZigBee protocol is deployed to form resilient, low-power mesh networks, supporting extensive spatial coverage in enclosed environments where power efficiency and communication reliability are critical [11]. LoRaWAN technology is integrated for long-range, low- data-rate wireless telemetry, enabling robust environmental data acquisition across large geographic footprints, optimal for city-wide and industrial estate monitoring [12]. Dedicated GSM or cellular modules serve remote sites by relaying data continuously to central monitoring places, especially where the local network is absent infrastructure.

B. Sensor Array Architecture

The optical particle counters measure the suspended particulate mass concentrations, PM2.5 and PM10, by using calibrated photometric analysis, thereby providing high-resolution input regarding urban and occupational air quality assessment [13].

Electrochemical analysers target trace gas species: CO_2, NO_2, VOCs, featuring integrated sampling cells and algorithmic compensation for cross-sensitivity to ensure selectivity and linearity of response [14]. Semiconductor platforms detect volatile organic compounds and carbon monoxide and are remarkable for their integration into miniaturised, modular data acquisition assemblies.

Capacitive humidity and thermometric transducers make basic environment baseline measurements used to normalize pollutant readings or adapt the control logic in dynamically changing conditions [10].

C. Calibration, Signal Validation, and Integrity Management

Instrumentation is exposed to periodic calibration against reference analysers in agreement with the regulatory specifications that guarantee measurement traceability, stability, and adherence to established standards [14]. Redundant, or co-located sensor cross-validation is performed at regular intervals in order to guard against drift and to validate the fidelity of the monitoring network. Automated quality assurance/quality control routines authenticate data prior to submission to centralized analytics using parametric thresholds and status indicators according to continuous monitoring regulatory frameworks.

D. Regulatory Conformance and Performance Benchmarking

Data streams are continuously benchmarked against normative standards of WHO, EPA, and NAAQS, substantiating compliance, documenting operational integrity, and driving regulatory reporting cycles. Periodic evaluation of aggregated datasets underpins spatial and temporal analytics for source attribution and intervention efficacy, thereby closing the loop on air quality management.

TABLE I: AIR QUALITY SENSOR TYPES AND MEASURED PARAMETERS

Sensor Type	Measured Parameter	Citation
Formaldehyde Sensor	HCHO	[1]
Pressure Sensor	Air Pressure	[2]
MEMS Hygrometer	Relative Humidity	[3]
Photoionization Detector	VOCs (wide range)	[4]
Ozone Sensor	O_3	[5]
Nitrogen Dioxide Sensor	NO_2	[1]
Noise Sensor	Acoustic Level	[6]
Light Sensor	Ambient Light	[3]
Multi-Sensor	PM, CO_2, VOCs, etc.	[7]

E. Processing and Control Logic

Microcontroller units embedded at each location manage sensor output acquisition, pre-filtering, and multiplexing. The generated signal processing algorithms identify threshold exceedance events that trigger ventilation and filtration subsystems according to requirements. Edge computing units pre-process onsite data to reduce latency and network overhead and provide analytics inputs for adaptive system control.

F. Purification System Integration

Multistage purifier trains containing HEPA filtration, catalytic substrates, and activated carbon are designed to reduce airborne pollutants by providing phase-specific removal efficiencies to support indoor air quality compliance [15]. These come into play during off-grid or distributed deployments of autonomous systems, powered by renewable sources like photovoltaic arrays-an example of energy optimization and sustainability at its best [16].

G. Information Delivery and Control Interface

Supervisory dashboards and mobile control panels provide end-users with real-time air quality metrics and historical data, visualizations, and maintenance alerts that support full-spectrum operational oversight and immediate remediation action. It provides system reliability through automated diagnostics and preventive maintenance notifications for timely sensor recalibration and consumable replacement.

III. COMPARISON OF PERFORMANCE

The modern indoor air quality management systems incorporate a range of sensor-based electronic technologies together with advanced engineering methods, thereby gaining substantial advantages over conventional mechanisms.

A. Sensor Technology and Detection Fidelity

The particulate and gaseous pollutant detections are enabled, correspondingly, by optical particle counters and electrochemical gas analyzers and NDIR sensors, respectively [1][2][3][4][10]. These components provide high specificities, while real-time detection limits for particulate matter and gases are generally within the microgram per cubic meter and parts-per-billion ranges, respectively. Precision is maintained through traceable multi-point calibration and continuous validation against reference-grade standards [3][16][4][13][14].

B. Data Acquisition, Connectivity, and Computational Efficiency

This can enable real-time, low-latency telemetry between widely dispersed sensor nodes and centralized data repositories using wireless architectures based on protocols like ZigBee, WiFi, and LoRaWAN [2][13][14]. Microcontroller-based edge computation can further enable preliminary data vetting, filtering out outliers, and transmitting over low-bandwidth, thus cutting latency and enabling higher temporal resolution.

C. Power Reliability and Sustainability

The integration of photovoltaic panels and hybrid storage ensures continuity in system operation, hence supporting long-term autonomous deployments even in grid-limited environments [7][8]. In this way, energy autonomy enhances the resilience of the system against external power disruptions, while decreasing the operational costs.

D. User Interaction and Information Accessibility

Presenting real-time air quality metrics, temporal trend analysis, and threshold exceedance alerts on dashboards, mobile applications, and local display panels [4][6][9][10][11], systematic maintenance notifications and indications of device status allow for servicing preventively to support long-term reliability.

E. Compliance, Validation, and Regulatory Benchmarking

Continuous acquisition and analyses of data can ensure compliance with WHO and EPA requirements along with local NAAQS, while timely interventions can be enabled by documented evidence to prove that the standards on health and safety have been met [17][3][8][11]. Features such as periodic calibration routines, comparative analysis with colocated reference monitors, and auto-validation cycles can assure continued precision [16][10][14].

F. Adaptive Purification and Control Systems

These HEPA H13/ULPA filtration, active carbon adsorption, and photocatalytic reactors are dynamically actuated by closed-loop control algorithms [4][5][9][12][15].
This approach enables responsive systems, which allow for a selective operating and activation mechanism, based on threshold exceedances informed by sensor inputs; hence energy consumption is minimized and wear of consumable material reduced [7][8].

TABLE II: EFFICIENCY OF ADAPTIVE AIR PURIFICATION SYSTEMS FOR DIFFERENT POLLUTANTS

System	Pollutant	Efficiency (%)	Reference
Solar-Powered HEPA	Particulates	70–83	[16]
IoT Polypropylene	PM2.5	87.5	[15]
Photocatalytic TiO2	VOCs	90	[18]
FGMLCS Control	Formaldehyde	57	[14]
Multi-stage Filter	Mixed Pollutants	75–80	[17]

G. Performance Advantages over Conventional Systems

E-technologies also allow for order-of-magnitude improvements in temporal and spatial resolution of air quality data, statistical reliability of pollutant measurements, and automated demand-driven purification efficiency. In this way, the approach is systematic, with a substantial reduction of pollutant exposure, while maintenance overhead is reduced and user engagement enhanced compared to traditional static or manually operated purification strategies.

IV. ANALYSIS AND DISCUSSION

The most recognized and methodologically robust air quality monitoring systems are engineered around IoT-based, sensor-driven platforms, driven by precise standards and relying on few consumer-grade wearables like smartwatches to ensure industrially scalable, accurate, and regulated solutions. Most of the air quality monitoring architectures involve industrial-grade sensors and protocols, such as ISO/IEC/IEEE 21451, which define interoperability, reliability, and strict standards of data across heterogeneous hardware and communication layers.
IoT-based air quality systems have rapidly evolved, proposing real-time, scalable monitoring for both indoor and outdoor environments [1][2].
Modern systems take advantage of multi-pollutant sensor arrays, including PM2.5, PM10, CO, NO2, O3, integrated with wireless networks such as LoRaWAN and 5G, as well as cloud platforms for centralized data storage and visualization [1][3]. Advances include the adoption of edge computing, AI, and machine learning models for data analytics, auto-calibration, and predictive alerts [4][1]. Hybrid deployment approaches involving stationary and mobile sensors (drones, vehicles) further improve granularity and increase spatial coverage [1]. Integration with digital dashboards, mobile apps, and public notification systems, such as SMS or billboards, promotes access and community engagement [4][1]. Most of the recent developments overcome previous limitations, such as static measurement sites, low response speed, and lack of adequate granularity in conventional monitoring networks [1][4][5].

A. Sensor Accuracy and Calibration

Low-cost sensors, which are being developed for use in large numbers, commonly suffer from problems with accuracy, drift, and cross-sensitivity, and thus require regular calibration and validation against reference-grade instruments [5][6].

B. Data Management and Reporting

Therefore, huge data streams bring challenges in real-time processing, cloud storage, standardization, and interoperability across different platforms and agencies [2].

C. Hardware and Connectivity Constraints

Sensor hardware can be bound by constraints in power consumption, weather resistance, and gaps in connectivity, especially in rural or remote areas [6].

D. Coverage and Scalability

While urban infrastructure makes deployment easier, sparse sensor networks in less-developed areas limit spatial resolution and comprehensive mapping [6][2].

E. Security and Privacy

Data transmission over public networks raises concerns in terms of cybersecurity threats-data hacking, spoofing-and potential privacy breaches [6].

F. Interpretation and Data Quality

Environmental complexity renders air quality data interpretation context-dependent, sometimes yielding misleading or overly simplified public health messages [6].

G. Cost

Although the cost of individual sensors is falling, scaling to full city-wide coverage, maintaining data reliability, and network maintenance can often be extremely expensive [6].

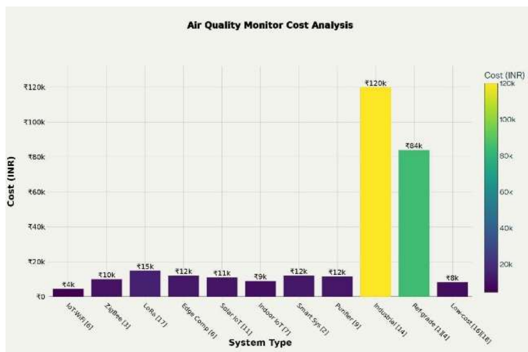

Fig.1 Air Quality Monitor Cost Analysis

V. Conclusion

This review highlights the fact that the evolution of air quality monitoring systems has been accelerated by the convergence in sensor miniaturization, IoT connectivity, edge computing, and renewable energy integration, thereby supporting both municipalities and industry to realize flexible, scalable, and data-rich environmental monitoring frameworks. Deployments from urban ZigBee- or LoRa-powered sensor networks to solar-driven IoT air purification platforms serve as evidence of both technical feasibility and the transformative potential of engineered solutions at improving indoor and outdoor air environments. Adoption of harmonized protocols such as ISO/IEC/IEEE 21451 facilitates interoperability, while cloud-based architectures offer robust analytics and predictive maintenance capabilities, timely responses to air pollution events, and improved public health outcomes.

Solutions such as compact IoT air purifiers, adaptive ventilation control for operating rooms, and nature-inspired greening strategies for indoor spaces illustrate that these can be tailored to operational requirements, cost constraints, and environmental targets. Challenges remain in ensuring sustained sensor accuracy, power autonomy, secure data transmission, and seamless integration of AI-driven insights with traditional control systems. Future developments to watch should include prolonging the operational life and reliability of sensor modules, further refining adaptive control methods for complex pollutant mixtures, and leveraging innovative purification mechanisms including photocatalytic sterilization and bio-filtration. Further engineering research is needed to address pathways to large-scale implementation, compliance with relevant standards, and the development of holistic urban air quality management platforms that will place these smart systems at the heart of foundational infrastructure for healthier, safer, and more sustainable living and working spaces around the world.

References

[1] World Health Organization. (2021). Household air pollution and health [Fact sheet]. World Health Organization: Geneva, Switzerland..

[2] Rahaman, T. (2025). Smart Environmental Monitoring Systems for Air and Water Quality Management. American Journal of Advanced Technology and Engineering Solutions, 1(01), 1-19.
[3] Wang, W., Yuan, Y., & Ling, Z. (2011, September). The research and implement of air quality monitoring system based on ZigBee. In 2011 7th International Conference on Wireless Communications, Networking and Mobile Computing (pp. 1-4). IEEE.K. Elissa, “Title of paper if known,” unpublished.
[4] Phala, K. S. E., Kumar, A., & Hancke, G. P. (2016). Air quality monitoring system based on ISO/IEC/IEEE 21451 standards. IEEE Sensors Journal, 16(12), 5037-5045.
[5] Marinov, M. B., Topalov, I., Gieva, E., & Nikolov, G. (2016, May). Air quality monitoring in urban environments. In 2016 39th International spring seminar on electronics technology (ISSE) (pp. 443-448). IEEE.
[6] Mishra, A. (2024). Edge Computing and IoT-Based Urban Environment Monitoring Solutions. Computational Engineering and Technology Innovations, 1(3), 139-149.
[7] Sung, W. T., & Hsiao, S. J. (2021). Building an indoor air quality monitoring system based on the architecture of the Internet of Things. EURASIP Journal on Wireless Communications and Networking, 2021(1), 153.
[8] Hung, F. H., Tsang, K. F., Wu, C. K., Liu, Y., Wang, H., Zhu, H., ...& Wan, W. H. (2020). An adaptive indoor air quality control scheme for minimizing volatile organic compounds density. IEEE Access, 8, 22357-22365.
[9] Vakharia, A., & Chavan, A. (2025, April). Development of a Compact IoT-Enabled Air Purification System for Indoor Air Quality Improvement. In 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM) (pp. 1115-1123). IEEE.
[10] Kumar, B. H., Prakash, N., Namitha, C., Chandana, H. R., Jeevan, G., & Manjunath, G. (2024, November). Solar Harmoni Air: The Integration of Solar Power for Intelligent Outdoor Air Purification and Monitoring System. In 2024 International Conference on Recent Advances in Science and Engineering Technology (ICRASET) (pp. 1- 6). IEEE.Khkh
[11] Jose, A., Abraham, C., Soman, A. K., TJ, A., Anandakrishna, A., & Shibu, A. (2024). IoT based solar powered air purifier with air quality monitoring system. In E3S Web of Conferences (Vol. 529, p. 04016). EDP Sciences.
[12] Duan, X., Huang, Y., Shen, C., Jones, P., & Deng, X. (2025). Study on the sterilization performance of photocatalysts used in indoor air purification. Indoor Air, 2025(1), 1071778.
[13] Shahid, S., Brown, D. J., Wright, P., Khasawneh, A. M., Taylor, B., & Kaiwartya, O. (2025). Innovations in Air Quality Monitoring: Sensors, IoT and Future Research. Sensors, 25(7), 2070.
[14] Hussein, O. D., & Osman, H. (2024). IoT-based air quality management in Somalia. International Journal of Electronics and Communication Engineering, 11(3), 77-86.
[15] Ganeshkumar, D., Parimala, V., Santhoshkumar, S., Vignesh, T., & Surendar, M. (2020). Air and sound pollution monitoring system using cloud computing. Int. J. Eng. Res., 9(6).
[16] Mata, T. M., Oliveira, G. M., Monteiro, H., Silva, G. V., Caetano, N. S., & Martins, A. A. (2021). Indoor air quality improvement using nature-based solutions: design proposals to greener cities. International journal of environmental research and public health, 18(16), 8472.
[17] Rosmiati, M., Rizal, M. F., Susanti, F., & Alfisyahrin, G. F. (2019). Air pollution monitoring system using LoRa modul as transceiver system. TELKOMNIKA (Telecommunication Computing Electronics and Control), 17(2), 586-592.
[18] Yi, W. Y., Lo, K. M., Mak, T., Leung, K. S., Leung, Y., & Meng, M.L. (2015). A survey of wireless sensor network based air pollution monitoring systems. Sensors, 15(12), 31392-31427.
[19] Yojana, A. C. (2021). IOT System To Control The Air Quality In Operating Room. Turkish Journal of Computer and Mathematics Education, 12(3), 5726-5732.