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IoT System for Indoor Air Quality Monitoring in Accordance with European and International Standards

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Abstract — **The Internet of Things (IoT) has facilitated the creation of affordable and dependable solutions for real-time environmental monitoring. This paper discusses the design and evaluation of a smart indoor air quality monitoring system that combines an M701 multifunctional air quality sensor with an ESP32 microcontroller. The system measures carbon dioxide, particulate matter ($PM_{2.5}$ and PM_{10}), formaldehyde, total volatile organic compounds, temperature, and relative humidity. Data from the sensor module are securely transmitted to the server using the Message Queuing Telemetry Transport (MQTT) protocol over Transport Layer Security (TLS), ensuring data integrity and confidentiality. Measurements were taken in a 30 m² office space under stable operating conditions. The results showed that most values remained within the limits recommended by international and European guidelines, although occasional exceedances were noted for formaldehyde and total volatile organic compounds. The system exhibited high reliability, stability, and scalability, making it suitable for integration into heating, ventilation, and air conditioning systems, as well as for implementing predictive analytics for proactive air quality management.**

Keywords - indoor air quality monitoring; Internet of Things (IoT); MQTT protocol; environmental monitoring; ESP32 microcontroller;

I. INTRODUCTION

Indoor Air Quality (IAQ) is acknowledged as a critical factor in protecting public health and well-being, particularly in urban settings and enclosed environments where individuals spend between 65% and 90% of their time [1]. Insufficient ventilation, the presence of indoor pollution sources (such as furniture, paints, and electrical appliances), and rising energy demands in buildings have been identified as contributors to the increased risk of exposure to harmful gases and particles [2].

a. Carbon dioxide (CO_2) – serves as an indirect indicator of ventilation efficiency and human occupancy. Concentrations exceeding 1000 ppm are regarded as indicative of inadequate air exchange and are associated with diminished cognitive performance, drowsiness, and headaches [3], [4].

b. $PM_{2.5}$ and PM_{10} – refer to fine and coarse suspended particles capable of penetrating deep into the respiratory system, with their presence linked to respiratory infections, asthma, cardiovascular diseases, and increased mortality [5].

c. Formaldehyde (CH_2O) – a volatile organic compound found in building materials, adhesives, and textiles. Prolonged exposure is associated with mucous membrane irritation and an elevated risk of cancer [6].

d. TVOC (Total Volatile Organic Compounds) – a cumulative measure of the concentration of volatile organic compounds emitted from paints, cleaning agents, plastics, and other materials; elevated levels can cause irritations and neurological effects [7].

e. Air temperature – a factor relevant to thermal comfort and productivity, although not formally included in air pollution directives [8].

f. Relative humidity – the optimal range of 40% to 60% is associated with reduced microbial growth and the maintenance of a healthy indoor microclimate [9].

The significance of IAQ monitoring was further underscored during the COVID-19 pandemic, with ventilation and CO_2 monitoring identified as key preventive measures in schools, offices, and public spaces [10]. Concurrently, the European Green Deal and the Corporate Sustainability Reporting Directive (CSRD) mandated extended ESG (Environmental, Social, Governance) reporting within EU Member States, including compulsory disclosure of environmental performance indicators [11]. Indoor air quality has been recognized as a pertinent criterion in international green building certification systems (such as Leadership in Energy and Environmental Design (LEED), WELL Building Standard (WELL), and RESET Air Standard (RESET)) [12] and is increasingly referenced as a significant component within Environmental, Social, and Governance (ESG) frameworks, particularly under the Environmental (ventilation efficiency, emission reduction) and Social (occupant health and well-being) dimensions [13].

In Bosnia and Herzegovina, the fundamental legal frameworks for environmental protection have been aligned with EU legislation through entity-level regulations. In the Federation of Bosnia and Herzegovina, the Law on Environmental Protection (Official Gazette of FBiH, No. 33/03 and 38/09) is currently in force [14], while in the Republic of Srpska, the Law on Environmental Protection (Official Gazette of RS, No. 71/12 and 79/15) is applicable [15]. Air quality monitoring and supervision are conducted by entity hydrometeorological institutes [16], [17], in accordance with methodologies consistent with EU directives and international standards. However, the practical implementation of these regulations is hindered by limited technical capabilities and insufficient inter-institutional coordination.

The deployment of IoT technologies has facilitated precise and energy-efficient real-time monitoring of key IAQ parameters, along with automated alerts for exceedances and a foundation for optimizing ventilation and energy consumption. The objective of this study was to develop and evaluate a monitoring system based on internationally recognized guidelines and reference threshold values from relevant regulatory frameworks, with the potential for deployment in public facilities, educational institutions, and smart buildings in Bosnia and Herzegovina and the broader region

II. Regulatory Framework and Guidelines for Indoor Air Quality

The measurement and management of indoor air quality (IAQ) are increasingly recognized as essential components within the regulatory frameworks of the European Union (EU) and international health organizations. While certain EU directives primarily focus on ambient (outdoor) air, their principles and limit values are frequently utilized as reference points for assessing indoor microclimates, particularly in relation to protecting vulnerable population groups and ensuring the energy efficiency of buildings.

This study focused on measuring parameters that are regarded as the most common indicators of air quality in typical office environments, which can be reliably monitored using the applied sensor module. These parameters include carbon dioxide (CO_2, ppm), particulate matter with an aerodynamic diameter of 2.5 micrometers or less ($PM_{2.5}$, µg/m³), particulate matter with an aerodynamic diameter of 10 micrometers or less (PM_{10}, µg/m³), formaldehyde (CH_2O, µg/m³), total volatile organic compounds (TVOC, µg/m³), air temperature (°C), and relative humidity (RH, %). These parameters were selected based on their inclusion in relevant international standards and guidelines, as well as their direct correlation with perceptions of air quality, thermal comfort, and occupant health [18].

Other pollutants, such as carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3), were not included in the measurements due to the limitations of the applied sensor module, which is not designed to detect them. However, reference values for these pollutants are defined in applicable regulatory documents [5].

Directive 2008/50/EC – Ambient Air Quality and Cleaner Air for Europe [19] serves as the principal EU legal act in the field of air pollution control, establishing limit values for key outdoor air pollutants that are often employed for indoor air quality assessments. The Energy Performance of Buildings Directive (EPBD) – 2024/1275, revised in 2024 [20], mandates EU Member States to ensure healthy indoor climates in new and renovated buildings through energy efficiency measures and the monitoring of fundamental air quality parameters.

For indoor environments, the most pertinent guidelines have been established by the World Health Organization (WHO), the European Committee for Standardization (CEN), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the International Organization for Standardization (ISO).

A. *WHO Global Air Quality Guidelines (2021)*

The WHO guidelines [21] set the international public health standards for air quality, including indoor environments. The recommended limit values relevant to this study are as follows:

a. $PM_{2.5}$: ⩽ 15 µg/m³ (24-hour mean) and ⩽ 5 µg/m³ (annual mean)

b. PM_{10}: ⩽ 45 µg/m³ (24-hour mean) and ⩽ 15 µg/m³ (annual mean)

c. Formaldehyde: ⩽ 100 µg/m³ (30-minute mean)

These values are generally more stringent than those established by European regulations and serve as a benchmark for public health protection.

B. *EN 13779:2007 – Ventilation for Non-residential Buildings*

The EN 13779:2007 standard [22], applicable to non-residential spaces such as offices, schools, and other work environments, specifies that CO_2 concentrations in indoor air should not exceed 1000 ppm for optimal conditions, while values exceeding 1500 ppm indicate insufficient ventilation.

C. *ASHRAE and ISO Standards*

The ANSI/ASHRAE 55-2023 standard [8] defines acceptable temperature ranges for work and administrative spaces as follows:

- Summer 23–26 °C (73–79 °F)
- Winter: 20–24 °C (68–75 °F)

The ISO 7730:2005 standard [23] provides a methodology for calculating and assessing thermal comfort, including the Predicted Mean Vote (PMV) index and the Predicted Percentage Dissatisfied (PPD). These parameters are categorized as comfort criteria rather than direct air pollution indicators and are part of the broader Indoor Environmental Quality (IEQ) framework [24], which encompasses thermal, acoustic, lighting, and air quality factors.

While there is no binding EU directive specifying particular relative humidity (RH) values, the ASHRAE 55 standard and recommendations from the WHO suggest maintaining indoor RH levels between 40% and 60%. This range is associated with a reduced risk of respiratory infections, allergic reactions, mold growth, and the release of chemical pollutants. RH levels below 40% increase the likelihood of mucous membrane dryness and heightened susceptibility to infections, whereas levels above 60% promote the growth of mold, fungi, and dust mites [25].

D. RESET Air Standard

Total Volatile Organic Compounds are a key indicator of indoor air quality, reflecting emissions from building materials, furnishings, cleaning agents, and occupant activities. The RESET Air Standard [26] defines performance thresholds for continuous IAQ monitoring, with TVOC concentrations $\leqslant$ 400 μg/m^3 classified as “good” and values approaching 1000 μg/m^3 considered the upper acceptable limit.

III. IoT Systems for Air Quality Monitoring

The Internet of Things (IoT) is defined as a distributed system of interconnected devices equipped with sensors, processing units, and communication modules, enabling the real-time collection, processing, and exchange of data via network protocols. Key characteristics of such systems include a high degree of automation, the capability to operate with high spatial and temporal resolution, scalability, and integration with information systems for analysis and management [27].

In the realm of indoor air quality monitoring, IoT technology facilitates continuous measurement of harmful gases and particulate matter concentrations, as well as microclimatic parameters such as temperature and relative humidity. This continuous monitoring allows for swift detection of deviations from recommended values, timely implementation of corrective measures, and the safeguarding of occupant health.

In contrast to traditional monitoring methods that rely on periodic sampling and laboratory analysis, the IoT approach offers continuous and automated monitoring without requiring constant user intervention. High measurement frequency enhances the accuracy of environmental condition evaluations, while the modular design of sensor networks allows for straightforward system expansion and the integration of new functionalities. Consequently, more efficient energy management is achieved through adaptive control of ventilation and air conditioning according to actual needs, while also enabling the application of advanced analytics and predictive models [28].

The implementation of IoT technology in air quality monitoring has demonstrated significant benefits across various types of facilities. In educational institutions, monitoring CO_2 and $PM_{2.5}$ concentrations assists in identifying room congestion and optimizing ventilation, thereby enhancing students' cognitive performance [29]. In healthcare facilities, continuous monitoring of Volatile Organic Compounds (VOCs), formaldehyde, and particulate matter is utilized to mitigate the risk of respiratory infections and cross-contamination [30]. In smart buildings, IoT systems are integrated with Heating, Ventilation, and Air Conditioning (HVAC) systems, facilitating automatic regulation of indoor conditions and optimization of energy consumption [28].

The architecture of an IoT-based air quality monitoring system is typically structured across multiple interconnected functional layers, as illustrated in the work of Mota et al. [31], which outlines a comprehensive implementation from sensor acquisition to cloud integration and user visualization. At the sensor layer, multiple measurement modules are deployed to detect relevant gases, particulates, and microclimatic parameters in indoor environments. The microcontroller layer subjects the collected data to preliminary processing, noise filtering, and anomaly detection, with temporary data storage. The communication layer, often based on the MQTT protocol [32], ensures reliable and low-latency message exchange between field devices and the central platform. The server-cloud layer facilitates permanent data storage, application of advanced analytical methods, and integration with automated ventilation and air conditioning control systems. At the user layer, web or mobile applications provide visualization of current and historical values, report generation, and alarm threshold configuration. This modular structure ensures system reliability, scalability, and interoperability, while allowing for adaptation to specific technical and regulatory requirements.

IV. System Architecture

The *AirPulse* air quality monitoring system (Fig. 1) has been developed as a distributed IoT solution that integrates a sensor module, a microcontroller unit, wireless communication, a server backend, and a user interface for data visualization. This functional integration enables continuous collection, processing, and analysis of data related to pollutants and microclimatic parameters in indoor environments. The system is designed to provide timely insights into changes in air quality, facilitating the implementation of corrective measures and improving the health and working conditions of building occupants.

Its modular design ensures compatibility with a variety of indoor environments, including offices, educational institutions, healthcare facilities, and residential buildings, while the scalability of its architecture allows for straightforward expansion to incorporate additional sensors or analytical functionalities.

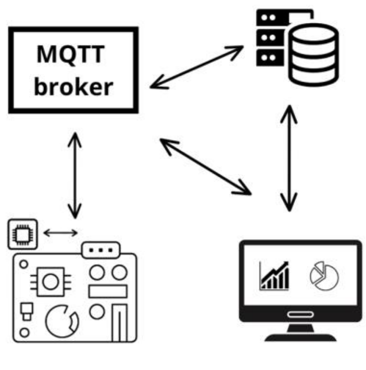

Figure 1. Block sheme of a system

The system employs the multifunctional M701 air quality sensor (Fig. 2), specifically designed for modern IoT applications and capable of simultaneously measuring gas concentrations, particulate matter, and essential microclimatic parameters. The sensor is configured with measurement ranges tailored for indoor environments, and readings are transmitted via a Universal Asynchronous Receiver-Transmitter (UART) interface, which is a widely utilized asynchronous communication standard [33]. During operation, data is sent serially to the microcontroller unit, where it is decoded and verified using a checksum. This methodology ensures stable transmission and broad compatibility with various microcontrollers while keeping implementation costs low.

At the core of the system is the ESP32-S3 microcontroller chip (Fig. 3), produced by Espressif Systems and optimized for high-performance IoT applications [34]. This chip features a dual-core Xtensa® LX7 processor operating at speeds up to 240 MHz, along with integrated support for Wi-Fi and Bluetooth LE communication, enabling simultaneous processing of sensor data and wireless transmission to the server infrastructure. The complete hardware setup, comprising the ESP32 microcontroller board and the M701 multifunctional air quality sensor module, is shown in Fig. 4.

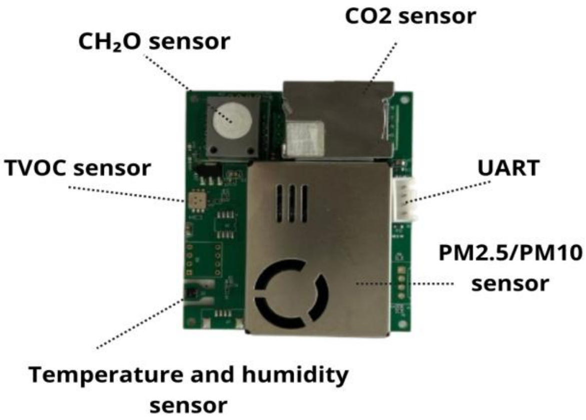

Figure 2. M701 air quality sensor module

Figure 3. ESP32-S3 microcontroller chip

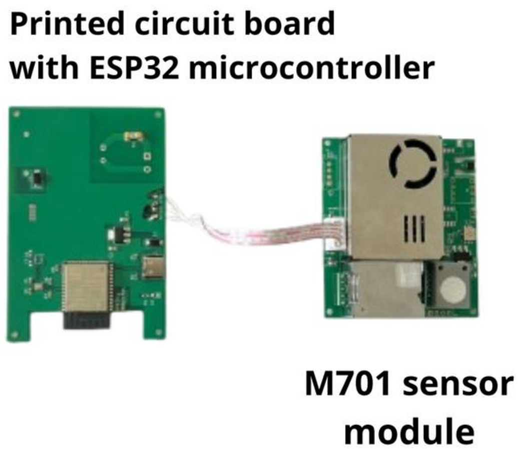

Figure 4. Complete hardware setup

In the air quality monitoring system, the ESP32-S3 manages data reception and parsing from the M701 sensor, constructs MQTT messages in JavaScript Object Notation (JSON) format, and establishes a secure Transport Layer Security (TLS) connection with a remote broker. Its energy efficiency, processing capabilities, and high level of communication function integration make it well-suited for continuous real-time operation.

For data exchange between sensor nodes and the central server system, the MQTT protocol—defined by the Organization for the Advancement of Structured Information Standards (OASIS) and optimized for IoT applications due to its low resource consumption, simple structure, and efficient publish/subscribe model—has been implemented [35]. In this system, a secure implementation of MQTT over TLS (commonly referred to as MQTTS) is utilized, employing TLS encryption and endpoint authentication to ensure data integrity and confidentiality [36]. The microcontroller device functions as an MQTT client, establishing a secure connection with the remote broker and publishing data to hierarchically organized topics, while the server application serves as a subscriber, receiving and processing the data asynchronously. Messages are structured in JSON format to ensure universal readability and facilitate future system expansion, with the Quality of Service (QoS) level configured according to the requirements for network reliability and availability [37]. This approach guarantees secure, efficient, and scalable data exchange between sensor devices and remote services in real-time.

The server-side component of the system has been developed in the Spring Boot environment [38], utilizing PostgreSQL for permanent data storage [39]. The backend application includes an MQTT client integrated with the broker service, which receives messages, validates them, and writes them to the database. The server application is decoupled from the client application, with communication facilitated through a Representational State Transfer Application Programming Interface (REST API) that enables secure retrieval of both real-time and historical measurements. On the user side, a web application developed in React.js [40] consumes the REST API to provide an interactive dashboard for displaying air quality parameters, featuring functionality for data filtering, report generation, and visualization of real-time measurements. The implemented user interface allows for secure user authentication, ensuring that only authorized users can access the platform.

After logging in, users are presented with a real-time view of all monitored parameters (Fig. 5) and access to historical measurements with date-range filtering (Fig. 6). This architecture guarantees flexibility in scaling, facilitates integration with additional services, and maintains a clear separation of concerns between data processing on the backend and presentation on the frontend.

V. EVAULATION OF MEASUREMENT RESULTS AND COMPLIANCE WITH INTERNATIONAL GUIDLINES

Measurements were conducted in an office environment with a floor area of 30 m² from 26 June to 29 July 2025, under stable sensor placement conditions, thereby ensuring the reliability and representativeness of the statistical indicators. For each monitored parameter, the mean value, minimum and maximum recorded values, and standard deviation (SD) were calculated. The standard deviation served as a statistical measure of the dispersion of values around the arithmetic mean, where lower values indicate more stable conditions and higher values reflect greater variability during the measurement period. In this analysis, the sample standard deviation was applied using Bessel's correction to obtain an unbiased estimate of the population standard deviation from a finite sample [41]. The formula (1) is expressed as:

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (1)$$

where n denotes the total number of observations, x_i the value of the i-th observation, and $\bar{x}$ the arithmetic mean of all observations.

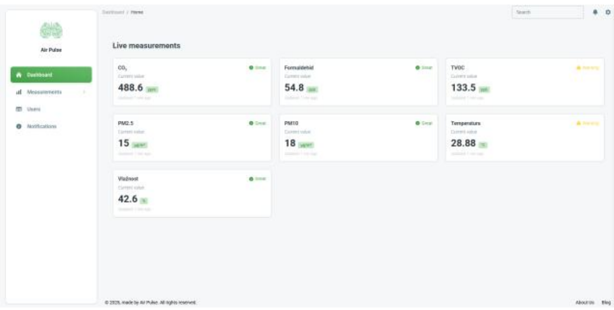

Figure 5. Real-time view of all monitored parameters after user login

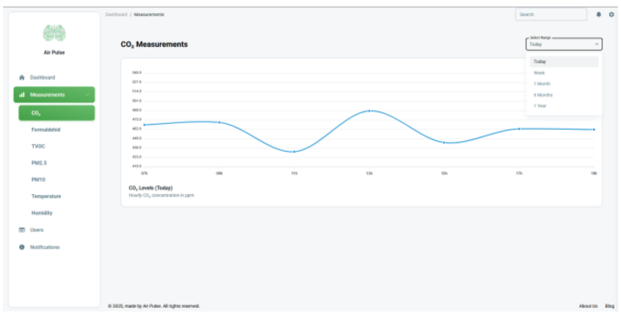

Figure 6. View of historical measurements with date-range filtering

The obtained results provided not only an assessment of the average air quality levels but also an indication of the variability of conditions, which is particularly relevant for determining compliance with applicable international guidelines and identifying potential exceedances of recommended thresholds.

A. *CO_2 Concentration*

The mean recorded CO_2 concentration was 544.39 ± 134.58 ppm, which, according to EN 13779:2007 [22], falls within the acceptable quality range (< 1000 ppm for optimal conditions). Peak values of up to 1011.80 ppm were observed as short-term episodes, most likely attributable to higher occupancy or insufficient ventilation. These occurrences were infrequent and did not constitute a continuous risk.

Table I presents the summary statistics for the CO_2 measurements obtained during the monitoring period.

B. *$PM_{2.5}$ and PM_{10} Particles*

Although the WHO Global Air Quality Guidelines (2021) [21] define limit values as 24-hour averages ($PM_{2.5}$: ⩽ 15 μg/m³; PM_{10}: ⩽ 45 μg/m³), instantaneous (spot) measurements were utilized in this analysis due to the system's high temporal resolution.

- $PM_{2.5}$: Mean concentration was 19.17 ± 5.68 μg/m³, with a maximum of 56.00 μg/m³. Occasional exceedances of the WHO recommended limit were predominantly associated with indoor activities (e.g., movement, ventilation).
- PM_{10}: Mean concentration was 23.38 ± 7.08 μg/m³, with a maximum of 69.20 μg/m³. Occasional exceedances of recommended thresholds were likely linked to particle resuspension from occupant activity.

Tables II and III present the summary statistics for the $PM_{2.5}$ and PM_{10} measurements obtained during the monitoring period.

TABLE I. SUMMARY STATISTICS FOR CO_2 MEASUREMENTS

Param	Average	Minimum	Maximum	Standard deviation
CO_2 (ppm)	544.39	420.20	1011.80	134.58
		08.07.2025. 07:54:08:23	02.07.2025. 14:51:40:05	

TABLE II. SUMMARY STATISTICS FOR $PM_{2.5}$ MEASUREMENTS

Param	Average	Minimum	Maximum	Standard deviation
$PM_{2.5}$ (μg/m³)	19.17	13.0	56.0	5.68
		27.07.2025. 23:28:06:87	15.07.2025. 13:24:56:11	

TABLE III. SUMMARY STATISTICS FOR PM_{10} MEASUREMENTS

Param	Average	Minimum	Maximum	Standard deviation
PM_{10} (µg/m³)	23.38	16.0 27.07.2025. 23:28:06:87	69.20 15.07.2025. 13:24:56:11	7.08

C. Formaldehyde (CH_2O)

The mean formaldehyde concentration was 45.42 ± 43.82 µg/m³, with a maximum recorded value of 255.70 µg/m³. Occasional exceedances of the WHO 30-minute guideline value of 100 µg/m³ [6] suggested episodic emissions from specific sources (e.g., construction materials, adhesives, cleaning agents). In these cases, additional investigation and enhanced ventilation were recommended.

Table IV presents the summary statistics for the CO_2 measurements obtained during the monitoring period.

D. Total Volatile Organic Compounds (TVOC)

The mean TVOC concentration was 233.28 ± 163.40 µg/m³, with most measurements falling within the acceptable range. However, peak values of up to 771.09 µg/m³ occasionally exceeded the threshold of 400 µg/m³ (classified as "good" according to the RESET Air Standard [26]) and approached the upper limit of 1000 µg/m³, indicating the influence of indoor pollution sources and user activities (e.g., use of cosmetics, cleaning).

Table V presents the summary statistics for the TVOC measurements obtained during the monitoring period.

E. Temperature and Relative Humidity

The mean temperature was 26.30 ± 2.90 °C and the mean relative humidity was 45.38 ± 5.01 %, indicating stable microclimatic conditions. The reference comfort ranges defined by ASHRAE 55-2023 [8] and ISO 7730:2005 [23] (20–26 °C and 40–60 % RH) were met in most instances, with minimal deviations. Relative humidity remained within the optimal range recommended for health benefits [9], associated with reduced microbial growth and chemical emissions. Minor variations were consistent with seasonal fluctuations in naturally ventilated spaces without active cooling.

TABLE IV. SUMMARY STATISTICS FOR CH_2O MEASUREMENTS

Param	Average	Minimum	Maximum	Standard deviation
CH_2O (µg/m³)	45.42	10.0 09.07.2025. 08:22:02:99	255.70 02.07.2025. 13:06:55:54	43.82

TABLE V. SUMMARY STATISTICS FOR TVOC MEASUREMENTS

Param	Average	Minimum	Maximum	Standard deviation
TVOC (µg/m³)	233.28	24.0 09.07.2025. 13:15:43:51	771.09 02.07.2025. 09:56:03:56	163.40

Tables VI and VII present the summary statistics for the temperature and relative humidity measurements obtained during the monitoring period.

VI. POTENTIAL FOR FUTURE DEVELOPMENT

The current implementation of the IoT-based indoor air quality monitoring system establishes a robust foundation for advanced environmental management solutions. Its modular and scalable architecture facilitates the integration of new capabilities without compromising system stability or current operational performance. A significant opportunity for enhancement involves integrating the system with HVAC systems, enabling real-time adjustments to ventilation and cooling based on continuously measured conditions. This approach would not only improve indoor air quality but also yield substantial energy savings through demand-controlled ventilation and optimized thermal regulation.

Another avenue for advancement includes the incorporation of additional sensing modalities—such as ozone, carbon monoxide, nitrogen dioxide, radon, acoustic parameters, and lighting conditions—thereby broadening the range of monitored environmental variables and facilitating deployment in environments such as hospitals, laboratories, classrooms, and other high-occupancy facilities. Moreover, applying machine learning and predictive analytics to accumulated datasets could provide deeper insights into pollutant dynamics, uncover recurrent patterns, and enable proactive interventions before guideline thresholds are exceeded.

Fig. 7 illustrates the conceptual design of an enhanced indoor environmental monitoring system, integrating additional sensing capabilities, HVAC control, and advanced analytics for comprehensive smart building management.

VII. CONCLUSION

This research culminated in the successful design, implementation, and evaluation of an Internet of Things (IoT)–based system for continuous indoor air quality monitoring. By integrating a multifunctional sensor module, a high-performance microcontroller platform, a secure wireless communication channel, and dedicated server-client software, a comprehensive and operational solution was established.

TABLE VI. SUMMARY STATISTICS FOR TEMPERATURE MEASUREMENTS

Param	Average	Minimum	Maximum	Standard deviation
Temp (°C)	26.30	18.19 02.07.2025. 07:25:39:94	31.84 01.07.2025. 13:45:16:57	2.90

TABLE VII. SUMMARY STATISTICS FOR HUMIDITY MEASUREMENTS

Param	Average	Minimum	Maximum	Standard deviation
Humidity (%)	45.38	35.55 01.07.2025. 17:12:59:09	59.88 01.07.2025. 23:36:40:78	5.01

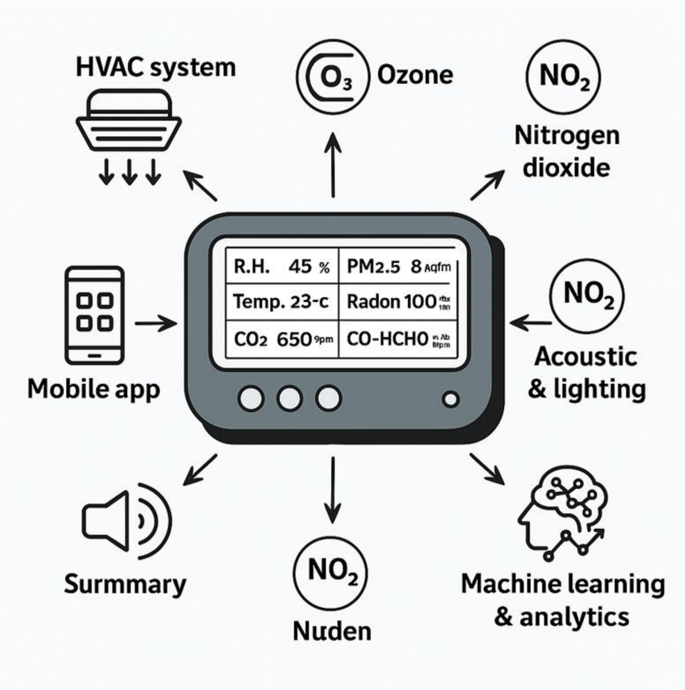

Figure 7. Conceptual design of system

The system was validated under real-world conditions, demonstrating stable operation, high data accuracy, and the capability for continuous monitoring.

The architectural approach employed, characterized by modularity and scalability, facilitates straightforward adaptation to various indoor environments and seamless integration into existing Building Management Systems (BMS). This flexibility ensures that the system can be configured to meet diverse operational requirements across educational institutions, administrative offices, healthcare facilities, and smart residential spaces.

In addition to its current capabilities, the system architecture is designed for future expansion, including integration with HVAC systems for automated environmental control, deployment of additional sensors for broader pollutant coverage, and the application of advanced data analytics for predictive modeling and anomaly detection. Such enhancements would further reinforce the system's role as both a preventive and proactive tool in maintaining optimal indoor conditions.

Overall, the implemented solution provides a technically robust and functionally reliable foundation for the wider adoption of IoT-based environmental monitoring. Its deployment can contribute to improved public health outcomes, enhanced energy efficiency, and alignment with contemporary regulatory, ESG, and sustainability frameworks, thereby advancing the adoption of data-driven environmental management practices.

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REFERENCES

[1] C. Schweizer, L. Edwards, I. Bayer-Oglesby, S. J. Gauderman, P. R. Bayer, P. Straehl, E. J. van Tongeren, and M. Jantunen, "Indoor time–microenvironment–activity patterns in seven regions of Europe," *J. Expo. Sci. Environ. Epidemiol.*, vol. 17, no. 2, pp. 170–181, 2007, doi: 10.1038/sj.jes.7500490.

[2] N. Canha, C. Mandin, O. Ramalho, et al., "Assessment of ventilation and indoor air pollutants in nursery and elementary schools in France," *Indoor Air*, vol. 26, no. 3, pp. 350–365, 2016, doi: 10.1111/ina.12222.

[3] U. Satish, M. J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, and W. J. Fisk, "Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance," *Environ. Health Perspect.*, vol. 120, no. 12, pp. 1671–1677, Dec. 2012, doi: 10.1289/ehp.1104789.

[4] CEN, *EN 13779:2007: Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems*. Brussels: European Committee for Standardization, 2007. [Online].Available:http://www.cres.gr/greenbuilding/PDF/prend/set4/WI_25_Pre-FV_version_prEN_13779_Ventilation_for_non-resitential_buildings.pdf [Accessed: Aug. 02, 2025].

[5] World Health Organization, *WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: WHO, 2021. [Online]. Available: https://www.who.int/publications/i/item/9789240034228. [Accessed: Aug. 09, 2025].

[6] World Health Organization, *WHO Guidelines for Indoor Air Quality: Selected Pollutants*. Copenhagen: WHO Regional Office for Europe, 2010.[Online].Available: https://www.who.int/publications/i/item/9789289041683.[Accessed: Aug. 07, 2025].

[7] Ľ. Mečiarová, Š. Vilčeková, E. Krídlová Burdová, and J. Kiselák, "Factors effecting the total volatile organic compound (TVOC) concentrations in Slovak households," Int. J. Environ. Res. Public Health, vol. 14, no. 12, p. 1443, Nov. 2017, doi: 10.3390/ijerph14121443.

[8] ASHRAE, ANSI/ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy. Atlanta, GA, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2023. [Online]. Available: https://blog.ansi.org/ansi/ansi-ashrae-55-2023-thermal-environmental-conditions/[Accessed: Aug. 11, 2025].

[9] A. V. Arundel, E. M. Sterling, J. H. Biggin, and T. D. Sterling, "Indirect health effects of relative humidity in indoor environments," *Environ. Health Perspect.*, vol. 65, pp. 351–361, 1986, doi: 10.1289/ehp.8665351.

[10] L. Morawska et al., "How can airborne transmission of COVID-19 indoors be minimised?," *Environ. Int.*, vol. 142, p. 105832, Sept. 2020, doi: 10.1016/j.envint.2020.105832.

[11] European Commission, The European Green Deal. Brussels, Belgium: European Commission, 2019. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en. [Accessed: Aug. 11, 2025].

[12] Measure of Quality, "IAQ, Green Building and ESG," Measure of Quality.[Online].Available:https://www.measureofquality.com/blog/iaq-green-building-esg. [Accessed: Aug. 12, 2025].

[13] TSI Incorporated, "How indoor environment monitoring supports ESG goals," TSI. [Online]. Available: https://tsi.com/indoor-environments/learn/how-indoor-environment-monitoring-supports-esg-goals.[Accessed: Aug. 20, 2025].

[14] "Zakon o zaštiti okoliša," *Službene novine Federacije BiH*, br. 33/03 i 38/09.

[15] "Zakon o zaštiti životne sredine," *Službeni glasnik Republike Srpske*, br. 71/12 i 79/15.

[16] Federalni hidrometeorološki zavod FBiH, "Kvalitet zraka – Monitoring i izvještaji." [Online]. Available: https://www.fhmzbih.gov.ba.[Accessed: Aug. 10, 2025].

[17] Republički hidrometeorološki zavod RS, "Informacije o kvalitetu vazduha." [Online]. Available: https://www.rhmzrs.com.[Accessed: Aug. 10, 2025].

[18] A. Loureiro, A. Ferreira, and N. Barros, "Systematic review of the literature on indoor air quality in healthcare units and its effects on health," BMC Public Health, vol. 25, Art. no. 2398, 2025, doi: 10.1186/s12889-025-23445-1.

[19] European Parliament and Council, *Directive 2008/50/EC on Ambient Air Quality and Cleaner Air for Europe*. Brussels, Belgium: EUR-Lex, 2008.[Online].Available:https://eur-lex.europa.eu/eli/dir/2008/50/oj/eng. [Accessed: Aug. 10, 2025].

[20] European Commission, *Energy Performance of Buildings Directive (EPBD)*, Directive 2024/1275. Brussels, Belgium: European Commission, 2024. [Online]. Available: https://energy.ec.europa.eu. [Accessed: Aug. 10, 2025]

[21] World Health Organization, *WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva, Switzerland: WHO, 2021. [Online].Available:https://www.who.int/publications/i/item/9789240034228. [Accessed: Aug. 10, 2025]

[22] European Committee for Standardization (CEN), EN 13779:2007: Ventilation for Non-Residential Buildings – Performance Requirements for Ventilation and Room-Conditioning Systems. Brussels, Belgium: CEN,2007.[Online].Available:http://www.cres.gr/greenbuilding/PDF/prend/set4/WI_25_Pre-FV_version_prEN_13779_Ventilation_for_non-resitential_buildings.pdf. [Accessed: Aug. 20, 2025].

[23] International Organization for Standardization, ISO 7730:2005 – Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. Geneva, Switzerland:ISO,2005.[Online].Available:https://www.iso.org/standard/39155.html. [Accessed: Aug. 08, 2025].

[24] S. Kubba, "Indoor Environmental Quality," in Handbook of Green Building Design and Construction: LEED, BREEAM, and Green Globes, 2nd ed. Oxford, UK: Butterworth-Heinemann (Elsevier), 2016, pp. 353–412, doi: 10.1016/B978-0-12-810433-0.00007-1.

[25] A. V. Arundel, E. M. Sterling, J. H. Biggin, and T. D. Sterling, "Indirect health effects of relative humidity in indoor environments," Environ. Health Perspect., vol. 65, pp. 351–361, 1986, doi: 10.1289/ehp.8665351. [Online].Available:https://pmc.ncbi.nlm.nih.gov/articles/PMC1474709. [Accessed: Aug. 13, 2025].

[26] RESET Air Standard: Continuous IAQ Performance Monitoring, RESET,2025.[Online].Available:https://www.reset.build/standard/air. [Accessed: Aug. 9, 2025].

[27] J. Saini, M. Dutta, and G. Marques, "Indoor Air Quality Monitoring Systems Based on Internet of Things: A Systematic Review," Int. J. Environ. Res. Public Health, vol. 17, no. 14, p. 4942, Jul. 2020, doi: 10.3390/ijerph17144942.[Online].Available:https://www.mdpi.com/1660-4601/17/14/4942. [Accessed: Aug. 13, 2025].

[28] B. John et al., "Monitoring Indoor Air Quality Using Smart Integrated Gas Sensor Module (IGSM) for Improving Health in COPD Patients," *Environmental Science and Pollution Research*, vol. 30, pp. 28889–28902, 2023, doi: 10.1007/s11356-022-24117-y.

[29] J. Pantelić, Y. R. Lin, and B. Sekhar, "Transformational IoT Sensing for Air Pollution and Thermal Comfort," *Frontiers in Built Environment*, vol. 8, 2022, doi: 10.3389/fbuil.2022.971523.

[30] M. R. García, A. Spinazzé, P. T. B. S. Branco, F. Borghi, G. Villena, A. Cattaneo, and S. I. V. Sousa, "Review of low-cost sensors for indoor air quality: Features and applications," *Applied Spectroscopy Reviews*, vol. 57, no. 9–10, pp. 747–779, 2022, doi: 10.1080/05704928.2022.2085734.

[31] A. Mota, L. Rodrigues, J. C. Ferreira, and A. J. Sousa, "Implementation of an Internet of Things Architecture to Monitor Indoor Air Quality: A Case Study During Sleep Periods," *Sensors*, vol. 25, no. 6, p. 1683, Mar. 2025, doi: 10.3390/s25061683.

[32] R. Giambona, A. E. C. Redondi, and M. Cesana, "MQTT+: Enhanced syntax and broker functionalities for data filtering, processing and aggregation," arXiv:1810.00773 [cs.NI], 2018. [Online]. Available: https://arxiv.org/abs/1810.00773.[Accessed: Aug. 12, 2025].

[33] Cubic Sensor and Instrument Co., Ltd., M701 Multi-in-One Air Quality Sensor Module – UART Data Sheet, 2022. [Online]. Available: https://en.gassensor.com.cn.[Accessed: Aug. 12, 2025].

[34] Espressif Systems, "ESP32-S3 Series Datasheet," 2023. [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32-s3_datasheet_en.pdf. [Accessed: Aug. 16, 2025].

[35] OASIS, *MQTT Version 3.1.1 Plus Errata 01*, Dec. 2015. [Online]. Available:https://docs.oasis-open.org/mqtt/mqtt/v3.1.1/os/mqtt-v3.1.1-os.html. [Accessed: Aug. 21, 2025].

[36] A. M. A. Al-Muqarm, A. Alkhafajee, A. H. Alwan, and Z. Alardawy, "Security and Performance Analysis of MQTT Protocol with TLS in IoT Networks," in Proc. Int. Conf. on Engineering Technology and their Applications (IICETA), Najaf, Iraq, Feb. 2022, doi: 10.1109/IICETA51758.2021.9717495.

[37] IBM, "Quality of service and connection management," IBM Integration Bus Documentation, 2025. [Online]. Available: https://www.ibm.com/docs/en/integration-bus/10.0.0?topic=bus-quality-service-connection-management. [Accessed: Aug. 9, 2025].

[38] Spring Framework, "Spring Boot," Spring Framework Projects. [Online]. Available: https://spring.io/projects/spring-boot.[Accessed: Aug. 9, 2025].

[39] PostgreSQL Global Development Group, "PostgreSQL Documentation," PostgreSQL,[Online].Available:https://www.postgresql.org/docs.[Accessed: Aug. 9, 2025].

[40] Meta, "React Documentation," Meta, [Online]. Available: https://react.dev. [Accessed: Aug. 9, 2025].

[41] D. S. Moore, G. P. McCabe, and B. A. Craig, Introduction to the Practice of Statistics, 9th ed. New York, NY, USA: W. H. Freeman, 2017.

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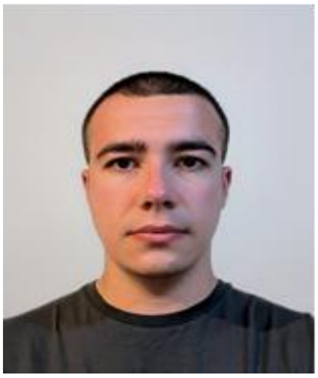

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