



Research Article

Development and Bench-Scale Functional Validation of a Low-Cost IoT Prototype for Classroom Environmental Quality Monitoring

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ABSTRACT

This study reports bench-scale functional validation of a low-cost IoT proof-of-concept for classroom environmental monitoring. A Raspberry Pi integrates DHT-22 temperature–humidity sensing, an MQ-135 used only as a non-specific gas/air-quality proxy, an LDR relative light sensor, Python/Tkinter software, and prototype actuators. Bench tests confirmed sensor acquisition and rule-based actuator triggering. No classroom field data, NDIR comparison, calibrated lux measurements, energy savings, or occupant outcomes are reported. The contribution is limited to functional system integration.

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Introduction

Indoor environmental quality (IEQ) in educational spaces includes interacting thermal, air-quality, visual, and acoustic factors. A major review of IEQ identifies thermal comfort, indoor air quality and ventilation, visual comfort, and acoustic comfort among the principal measurable and actively controllable components of indoor environments [1]. Field evidence from 42 primary schools in Cyprus further illustrates the need for environmental monitoring: during the May–July campaign, 85% of occupied school time exceeded the study’s recommended upper indoor-temperature limit of 27 °C, and one third of 24-h indoor PM2.5 measurements exceeded 15 µg/m³ [2]. These findings support the value of continuous environmental observation in educational buildings, while also showing that field conditions are influenced by occupancy, ventilation practice, and outdoor conditions.

Recent classroom studies show the value of continuous, sensor-based monitoring when the measured variables and instruments are appropriate for the intended claim. Sørensen and Kristensen [3] collected time-resolved CO₂ and TVOC data across 75 classrooms and identified ventilation type as an important factor affecting both measurements. At district scale, Ge et al. [4] analyzed data from 3,659 classroom monitors in 125 school buildings and demonstrated the usefulness of threshold-based visualization of continuous monitoring data for school decision-making. These studies are field deployments using calibrated or purpose-designed instrumentation; they therefore represent a validation level beyond the bench-scale prototype reported here.

Automation can also connect environmental sensing with operational actions, but performance claims require quantitative field evidence. In ten classrooms, Budhiyanto and Chiou [5] evaluated an HDR-image-based lighting and daylighting control system and reported approximately 43–63% lighting-energy savings while maintaining visual comfort for most participants. Canals Casals et al. [6] used temperature and CO₂ in an optimization framework for educational spaces and reported that coordinated control can reduce modeled energy demand. These results motivate integrated sensing and control. However, the present study does not measure energy savings and does not claim equivalent field performance.

The purpose of this study is therefore limited to the design and bench-scale functional validation of a compact, low-cost IoT prototype for environmental monitoring and local actuation. The prototype combines temperature–humidity sensing, a non-specific gas/air-quality proxy, relative light-level sensing, Raspberry Pi edge processing, Python-based rule logic, and a touchscreen interface. Its intended contribution is the demonstration of an integrated sensing–

decision–actuation architecture that can be reproduced and further developed. Real-classroom environmental improvement, calibrated pollutant concentration, lighting-standard compliance, energy savings, and occupant comfort are outside the evidential scope of the present pilot.

2. Literature Review

Continuous indoor monitoring is useful because environmental conditions vary substantially between buildings, rooms, ventilation strategies, and periods of occupancy. Konstantinou et al. [2] used low-cost sensors to measure temperature, relative humidity, particulate matter, CO₂, and VOCs in 42 primary schools. Sørensen and Kristensen [3] likewise used time-resolved low-cost measurements across 75 classrooms and reported that ventilation type was a key factor influencing CO₂ and TVOC concentrations. These field studies demonstrate both the value of continuous measurements and the importance of selecting sensing technologies that are appropriate for the variable being reported.

Low-cost sensing also requires validation and quality assurance. Gabriel et al. [7] deployed calibrated low-cost sensors for CO₂, temperature, relative humidity, and particulate matter in 84 homes and reported strong correlations with reference equipment, while also identifying long-term signal degradation in the particulate channel. This evidence is especially relevant to the present prototype because it shows that affordability alone does not establish measurement validity. Reference comparison, calibration, aging assessment, and quality-control procedures are required before low-cost measurements are interpreted quantitatively.

For school ventilation assessment, Clinchard et al. [8] continuously measured CO₂ before and after renovation in 48 school buildings and used identified build-up and decay periods to estimate air-change-related metrics. Ge et al. [4] similarly demonstrated the decision value of large continuous classroom datasets. These studies indicate the type of time-series evidence such as threshold exceedance, build-up, decay, and recovery behavior, that would be required to evaluate the present concept at classroom scale. Such field time-series data were not collected in this pilot. Control strategies in educational environments must also consider timing and equipment constraints. Canals Casals et al. [6] reported that temperature and CO₂ should be considered jointly in educational-space control and found that short control time steps were important in their modeled cases. In a field study, Rawat et al. [9] used visual and visual-acoustic CO₂ feedback to influence natural-ventilation behavior and reported reductions in classroom CO₂, while also noting a trade-off with energy use during

cold weather. These findings reinforce the need to evaluate environmental benefit and energy consequences together in future field deployment.

Lighting provides a complementary example of why sensing accuracy and field validation matter. Budhiyanto and Chiou [5] evaluated a classroom lighting and daylighting control system using HDR-image-derived luminance information, classroom experiments, and user questionnaires. Their system reduced lighting energy consumption by approximately 43–63% while maintaining visual comfort for most participants. The present LDR-based prototype is substantially simpler and was not calibrated against a lux meter; accordingly, it is used only to demonstrate relative light-response control rather than compliance with a lighting standard or a quantified energy-saving outcome.

Taken together, the literature distinguishes three levels that should not be conflated, (i) proof-of-concept integration, (ii) calibrated measurement, and (iii) field performance evaluation. Low-cost IoT hardware can support the first level, whereas quantitative air-quality, lighting, comfort, or energy claims require calibration and sustained real-environment measurements. This distinction is central to the revised scope of the present work.

Against this background, the present study contributes at the proof-of-concept level. It integrates multiple low-cost sensing channels, local edge processing, a graphical interface, and actuator outputs in a single bench-scale platform. The study asks whether the proposed sensing–decision–actuation chain can be implemented on commodity hardware and operated as an integrated prototype. It does not ask, and the available data cannot establish, whether the device improves air quality or comfort in a full-size classroom.

3. Methodology

The prototype comprises two implementation layers: a software layer for data acquisition, visualization, rule-based decision logic, and actuator commands, and a hardware layer containing sensors, the Raspberry Pi controller, and bench-scale actuators. This division is an implementation description rather than a literature-dependent methodological claim.

3.1 Software Architecture

The software stack is implemented in Python to integrate sensor input/output, rule-based control, data handling, and a lightweight graphical user interface (GUI). A Tkinter interface allows the operator to view current sensor states and apply local manual overrides. The software was developed for functional prototype operation. No formal

usability study or long-term software reliability test was conducted.

3.2 Hardware Platform

Temperature, relative humidity, a non-specific gas/air-quality proxy, and relative light level are acquired by low-cost sensors and processed by a Raspberry Pi 4 Model B. The Raspberry Pi was selected because it can run the Python application and graphical interface while providing general-purpose input/output for prototype peripherals. The platform choice is an engineering implementation decision and is not presented as a comparative performance result.

3.3 Environmental Quality Criteria and Control Logic

The control logic was designed for functional bench testing rather than for commissioned classroom operation. Consequently, the prototype demonstrates the structure of threshold-based and hysteresis-based actuation, but it does not establish classroom-valid environmental limits.

Air quality proxy

The MQ-135 channel is treated only as a non-specific gas/air-quality proxy. No CO₂ concentration, CO₂-equivalent value, or ppm value is reported from the MQ-135 in this revision because the sensor was not compared with a reference NDIR instrument. The prototype software uses changes in the sensor signal to demonstrate threshold-triggered actuation. A hysteresis concept separates activation and deactivation conditions to reduce rapid switching, but the exact numerical threshold values used during the original bench checks were not preserved in the archived pilot materials and are therefore not reported or reconstructed.

Relative light-level control

The LDR channel is used as a relative light-level input for functional control. Because the LDR was not calibrated against a traceable lux meter, the present prototype does not claim illuminance accuracy or compliance with lighting requirements. For future classroom commissioning, lighting criteria should be specified with reference to TS EN [10], which addresses lighting requirements for indoor workplaces. The bench prototype only demonstrates that a change in the light-sensor signal can be used to command the lighting output.

Thermal environment (temperature and humidity)

Temperature and relative humidity from the DHT-22 are used to demonstrate thermal-control triggering. The present pilot did not calculate PMV/PPD and did not

establish a classroom thermal-comfort category. Future field commissioning should use a thermal-comfort framework such as ISO [11] and/or the indoor-environment criteria of EN [12]. The exact numerical ON/OFF set points applied during the original bench checks were not retained in the archived records; therefore, this revision does not invent or retrospectively assign values.

Thresholds and hysteresis bands are software-configurable. However, because this work remained a small-scale pilot and the original numerical bench settings were not archived together with a synchronized test dataset, reproducible numerical set points cannot be reported from the available materials. This is a methodological limitation. No classroom-specific set point is claimed, and future experiments must document every ON threshold, OFF threshold, hysteresis band, sampling interval, and recovery criterion before data collection.

3.4 Operating Modes and Human Override

In automatic mode, the controller evaluates the available sensor signals and issues prototype actuator commands. The interface also permits manual override for functional testing. An automatic lights-off routine was implemented conceptually in the control logic. Because no classroom schedule was used in field operation, these functions are reported only as software/prototype capabilities rather than measured energy-saving features [5].

3.5 Sensors and Peripheral Hardware

The prototype includes three main sensing modules: a gas/air-quality proxy channel, a relative light-level channel, and a temperature–humidity channel, all connected to the Raspberry Pi edge controller.

Air-quality sensing

An MQ-135 metal-oxide (MOX) sensor is used as a low-cost, non-specific gas/air-quality proxy. Published descriptions of the MQ-135 characterize it as a tin-dioxide semiconductor sensor responsive to multiple gases rather than a selective CO₂ instrument [13]. In this study, its output is therefore interpreted only as a relative signal for functional actuation. No NDIR reference comparison was available, so no absolute concentration or gas-selectivity claim is made. A future version should replace or supplement this channel with a calibrated NDIR CO₂ sensor and, where required, dedicated TVOC or particulate sensors.

Relative light-level sensing

A light-dependent resistor (LDR) is connected through a simple readout circuit and used to detect relative changes in light level. The signal is used for prototype lighting actuation. Because no calibrated lux reference was used, the output is not converted into validated lux values and is not used to demonstrate compliance with TS EN [10].

Temperature and humidity

A DHT-22 digital sensor is used to acquire air temperature and relative humidity for the prototype. Measurements are read at fixed software intervals and used as inputs to the rule-based actuation logic. The present study did not perform a traceable calibration of the DHT-22 against a reference thermometer/hygrometer, so the results are treated as functional sensor inputs rather than metrological validation.

The sensors were installed within the small bench-scale prototype arrangement and positioned to reduce direct interference from the actuator and local heat sources where practicable. This arrangement is not representative of standard classroom sensor placement. Future field deployment must define sensor height and location, avoid local drafts and radiant sources, and document calibration and quality-control procedures.

The main sensing and control parameters are summarized in Table 1, which lists sensor types, operating principles, nominal characteristics, and associated control functions.

The prototype integrates the sensing channels and actuator outputs through a Raspberry Pi 4 Model B. The small Maglev fan used in the prototype is an actuator demonstrator for the control signal path; it is not presented as a ventilation device capable of servicing a 150–200 m³ classroom. Fan flow rate, room air-change rate, and full-scale ventilation effectiveness were not measured. The prototype configuration is summarized in Table 1.

Table 1. Sensors and variables used in the bench-scale IoT prototype

Variable	Sensor	Principle	Nominal range / notes	Purpose in control
Gas / air-quality proxy	MQ-135	MOX multi-gas sensing	Relative signal only; no NDIR reference comparison and no CO2 ppm claim	Demonstrate threshold-triggered actuator path
Relative light level	LDR (10 mm)	Photoconductive	Relative response only; not calibrated against a lux meter	Demonstrate light-responsive control
Air temperature & RH	DHT-22 (AM2302)	Digital temperature/RH sensing	Used as prototype input; no traceable reference calibration in this pilot	Demonstrate thermal/humidity rule logic

4. Results and Discussion

The bench-scale prototype demonstrated the intended functional sequence of sensing, rule evaluation, and actuator triggering. These checks establish implementation feasibility only. No uninterrupted real-classroom dataset was obtained, and the study therefore cannot quantify environmental improvement, threshold exceedance duration, recovery duration, energy savings, or occupant response.

4.1 Functional Validation

During bench checks, deliberate changes around the sensors produced corresponding software state changes and actuator commands for the MQ-135 air-quality-proxy channel, the DHT-22 temperature–humidity channel, and the LDR light-level channel. However, the original pilot did not archive a synchronized, multi-day time series with event timestamps. Consequently, response time, recovery time, overshoot, cycling frequency, and statistical repeatability cannot be reported quantitatively. The observation that the control chain executed as intended should therefore be interpreted as qualitative functional validation, not performance validation.

4.2 Air-Quality Control and Sensor Suitability

The MQ-135 channel generated a usable variable signal for bench-scale threshold testing, but the study did not determine gas selectivity or absolute concentration. Because there was no reference NDIR comparison, all CO2-specific interpretation has been removed from the prototype results. This limitation is important: a multi-gas MOX sensor can demonstrate the electronics and control path, but it cannot substitute for a calibrated, selective instrument when a scientific claim is expressed in ppm or when ventilation performance is evaluated.

4.3 Lighting Performance and Comparison

The LDR channel responded to changes in incident light and was able to trigger the prototype lighting output. No calibrated lux meter was used, so the test does not demonstrate illuminance accuracy or compliance with TS EN [10]. By contrast, Budhiyanto and Chiou [5] evaluated an instrumented classroom lighting-control system in ten classrooms and reported quantified energy and visual-comfort outcomes. The difference in validation level is emphasized here to avoid transferring those field results to the present bench prototype.

Accordingly, the LDR result supports only the feasibility of relative light-responsive control in a low-cost prototype. Energy consumption of the lighting load and of the complete IoT system was not measured; therefore, no net energy-saving claim is made. A future energy assessment must include the controller, sensor heaters, display, actuators, and controlled loads over the same observation period.

4.4 Integration and Usability

The prototype supported both automatic control logic and local manual override through the touchscreen interface. The functions were operable during bench testing, but no structured usability study with teachers, students, or facility personnel was conducted. The manuscript therefore reports interface functionality rather than improved user experience or human-factors performance.

4.5 Scope of Inference and Required Field Validation

The main implication of this pilot is methodological rather than performance-based. Field studies such as Ge et al. [4], Clinchard et al. [8], and Rawat et al. [9] illustrate the level

of sustained, calibrated classroom data needed to evaluate exceedance, recovery, ventilation response, and operational trade-offs. The present prototype has not reached that validation stage. A publishable field-performance extension would require several days or longer of uninterrupted classroom monitoring, reference instrumentation, fully documented numerical set points, and simultaneous logging of sensor values and actuator states.

5. Conclusions

In this study, a low-cost IoT prototype for environmental monitoring and local actuation was developed and functionally tested at bench scale. The system combined a Raspberry Pi, Python-based control software, a DHT-22 sensor, an MQ-135 non-specific gas/air-quality proxy, an LDR relative light-level sensor, a touchscreen interface, and prototype actuators. The bench checks demonstrated the feasibility of the sensing–decision–actuation chain. They did not validate real-classroom environmental performance.

The results support a narrower conclusion: commodity hardware can be integrated into a reproducible proof-of-concept platform for testing environmental control logic before field deployment. Because energy use, room-scale ventilation, calibrated illuminance, pollutant concentration, and occupant outcomes were not measured, the study does not demonstrate energy savings, improved classroom air quality, or thermal/visual comfort.

Several limitations are decisive. First, validation was restricted to a small bench-scale arrangement; no real-classroom measurements were collected under occupancy, weather, or operational variability. Second, the MQ-135 was not compared with a reference NDIR instrument, so it is reported only as a non-specific gas/air-quality proxy and no CO₂ concentration is claimed. Third, the LDR was not calibrated against a lux meter and the DHT-22 was not traceably calibrated against reference instruments. Fourth, the original numerical ON/OFF thresholds and hysteresis bands were not preserved in the archived pilot records and cannot be reproduced in this revision without fabrication. Fifth, no uninterrupted time-series dataset was retained, so exceedance, response, and recovery durations cannot be calculated. Sixth, the Maglev fan was only a bench actuator; its flow rate and air-change effectiveness for a classroom were not assessed. Finally, system power consumption, controlled-load energy use, net energy balance, and occupant usability were not measured.

Future work should begin with a fully documented test protocol. A calibrated NDIR CO₂ instrument and reference lux meter should be added, and temperature–humidity sensing should be checked against reference instrumentation. Every sampling interval, ON/OFF

threshold, hysteresis band, and recovery criterion should be fixed and reported before testing. Thermal-comfort interpretation should follow ISO [11] and/or EN [12], while lighting design and verification should follow TS EN 12464-1:2021. The next validation stage should record synchronized sensor and actuator time series for several uninterrupted days in a real classroom, enabling calculation of exceedance and recovery durations, cycling behavior, ventilation response, and energy balance.

In sum, this work establishes only a bench-scale proof of concept for an integrated low-cost IoT monitoring and actuation architecture. Its value lies in demonstrating system integration and identifying the measurements that are still required before classroom effectiveness can be claimed. Field deployment and reference-calibrated sensing remain necessary to convert the prototype into a validated classroom environmental-control study.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, Resources, Investigation, Methodology, Formal analysis, Writing – original draft, Visualization, Editing.

Author-2: Resources, Investigation, Validation Visualization, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Datasets are available on request. Available prototype documentation and retained bench records are available from the authors on reasonable request.

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References

- [1] I. Mujan, A. S. Anđelković, V. Munćan, M. Kljajić, and D. Ružić, “Influence of indoor environmental quality on human health and productivity - A review,” *Journal*

- of *Cleaner Production*, vol. 217, pp. 646-657, 2019, doi: 10.1016/j.jclepro.2019.01.307.
- [2] C. Konstantinou, A. Constantinou, E. G. Kleovoulou, A. Kyriacou, C. Kakoulli, G. Milis, M. Michaelides, and K. C. Makris, "Assessment of indoor and outdoor air quality in primary schools of Cyprus during the COVID-19 pandemic measures in May-July 2021," *Heliyon*, vol. 8, no. 5, Art. no. e09354, 2022, doi: 10.1016/j.heliyon.2022.e09354.
- [3] S. B. Sørensen and K. Kristensen, "Low-cost sensor-based investigation of CO₂ and volatile organic compounds in classrooms: Exploring dynamics, ventilation effects and perceived air quality relations," *Building and Environment*, vol. 254, Art. no. 111369, 2024, doi: 10.1016/j.buildenv.2024.111369.
- [4] B. Ge, K. Tieskens, P. Vyas, M. P. Botana Martinez, Y. Yuan, K. H. Walsh, L. Main, L. Bolton, M. Yajima, and M. P. Fabian, "Decision tools for schools using continuous indoor air quality monitors: A case study of CO₂ in Boston Public Schools," *The Lancet Regional Health - Americas*, vol. 48, Art. no. 101148, 2025, doi: 10.1016/j.lana.2025.101148.
- [5] A. Budhiyanto and Y.-S. Chiou, "Visual comfort and energy savings in classrooms using surveillance camera derived HDR images for lighting and daylighting control system," *Journal of Building Engineering*, vol. 86, Art. no. 108841, 2024, doi: 10.1016/j.jobbe.2024.108841.
- [6] L. Canals Casals, A. Alegria-Sala, N. Bonet, and M. Macarulla, "Educational environments' energy demand optimization based on indoor CO₂ concentration and temperature: Together better than separately," *Building and Environment*, vol. 266, Art. no. 112121, 2024, doi: 10.1016/j.buildenv.2024.112121.
- [7] M. F. Gabriel, G. Marques, D. Filipe, F. Felgueiras, J. P. Cardoso, J. Azeredo, G. Kazdaridis, P. Symeonidis, S. Keranidis, P. Conradie, I. Azevedo, and F. Anagnostopoulos, "Implementation of an IoT architecture for promoting healthy air quality in homes of families with children," *Building and Environment*, vol. 266, Art. no. 112040, 2024, doi: 10.1016/j.buildenv.2024.112040.
- [8] S. Clinchard, U. Haverinen-Shaughnessy, and R. Shaughnessy, "Assessing ventilation performance in schools using continuous CO₂ monitoring: Insights from renovation projects," *Building and Environment*, vol. 269, Art. no. 112406, 2025, doi: 10.1016/j.buildenv.2024.112406.
- [9] N. Rawat, P. Kumar, S. Hama, N. Williams, and A. Zivelonghi, "Improving classroom air quality and ventilation with IoT-driven acoustic and visual CO₂ feedback system," *Science of the Total Environment*, vol. 980, Art. no. 179543, 2025, doi: 10.1016/j.scitotenv.2025.179543.
- [10] *Light and lighting - Lighting of work places - Part 1: Indoor work places*, TS EN 12464-1:2021, 2021.
- [11] *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*, ISO 7730:2025, 2025.
- [12] *Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6*, EN 16798-1:2019, 2019.
- [13] F. N. Abbas, I. M. Saadoon, Z. K. Abdalrdha, and E. N. Abud, "Capable of gas sensor MQ-135 to monitor the air quality with Arduino Uno," *International Journal of Engineering Research and Technology*, vol. 13, no. 10, pp. 2955-2959, 2020, doi: 10.37624/IJERT/13.10.2020.2955-2959.