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# POTENTIAL OF A LOW-COST SYSTEM FOR MEASURING INDOOR ENVIRONMENTAL QUALITY IN LATIN AMERICAN EXTREME CLIMATES TOWARDS ENERGY EQUITY

# POTENCIAL DE UN SISTEMA DE BAJO COSTO PARA MEDIR LA CALIDAD AMBIENTAL INTERIOR EN CLIMAS EXTREMOS LATINOAMERICANOS HACIA LA EQUIDAD ENERGÉTICA

# POTENCIAL DE UM SISTEMA DE BAIXO CUSTO PARA MEDIR A QUALIDADE AMBIENTAL INTERIOR EM CLIMAS EXTREMOS DA AMÉRICA LATINA VISANDO A EQUIDADE ENERGÉTICA

**Claudia Eréndira Vázquez-Torres**
Doctora en Arquitectura
Posdoctorante de la Facultad de Ingeniería, Laboratorio de Modelado y Optimización de Procesos Energéticos y Ambientales
Universidad Autónoma de Yucatán, Mérida, México
https://orcid.org/0000-0002-5388-0780
claudia.vazquez@correo.uady.mx (Autor de Correspondencia)

**Renán Gabriel Quijano-Cetina**
Doctor en Ingeniería
Profesor Investigador, Facultad de Ingeniería
Universidad Autónoma de Yucatán, Mérida, México
https://orcid.org/0000-0001-9515-9249
renan.quijano@correo.uady.mx

**Israel Sánchez-Domínguez**
Doctor en Ingeniería
Técnico Académico Titular B TC, Unidad Académica del IIMAS en Yucatán
Universidad Nacional Autónoma de México, Mérida, México
https://orcid.org/0000-0002-7040-9552
israel.sanchez@iimas.unam.mx

**Bassam Ali**
Doctor en Ingeniería
Profesor Investigador, Facultad de Ingeniería, Laboratorio de Modelado y Optimización de Procesos Energéticos y Ambientales
Universidad Autónoma de Yucatán, Mérida, México
https://orcid.org/0000-0001-7526-6952
baali@correo.uady.mx

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# ABSTRACT

Public health has multidisciplinary challenges involving a combination of physical, mental, and social welfare. Two limitations to quantifying indoor pollutants (gases, chemical compounds, and suspended particles) are the high cost and the complexity of available measurement systems. Under this scenario, an experimental approach was used to develop a low-cost system to measure variables that affect human and environmental health. Calibration, validation, and technical adjustment processes were conducted in an extreme-climate location in southern Mexico, following domestic and international standards. The key results showed the feasibility of using low-cost tools to measure pollutants in developing countries. 57% of the data for H2S had a result above 150 ppm, which is considered harmful to human health. On the other hand, developing the measurement system in the studied locality showed the importance of having data to measure environmental pollution levels according to each region's habits and customs. Sensors and open access systems were used as these can directly benefit resource-constrained researchers and the public and private sectors interested in measuring environmental and comfort variables to promote universal access to knowledge.

Keywords
environmental measurement system, low-cost sensors, indoor environmental quality, pollutant measurement.

# RESUMEN

La salud pública presenta retos multidisciplinares que implican una combinación entre el bienestar físico, mental y social. Dos limitaciones para cuantificar los contaminantes en interiores (gases, compuestos químicos y partículas en suspensión) son el elevado coste comercial y la complejidad de los sistemas de medición disponibles. En este escenario, se utilizó un enfoque experimental para desarrollar un sistema con sensores de bajo coste para medir variables que influyen en la salud humana y ambiental. Los procesos de calibración, validación y ajuste técnico se realizaron en una localidad de clima extremo en el sur de México, bajo estándares nacionales e internacionales. Los resultados principales mostraron la viabilidad del uso de herramientas de bajo coste para medir contaminantes en países en vías de desarrollo. El 57 % de los datos de H2S mostraron un rendimiento superior a 150 ppm, lo que se considera perjudicial para la salud humana. Por otro lado, el proceso de desarrollo del sistema de medición en la localidad de estudio demostró la importancia de disponer de datos para medir los niveles de contaminación ambiental según los hábitos y costumbres de cada región. Los sensores y sistemas de acceso abierto se utilizaron para beneficiar directamente a investigadores con recursos limitados y a los sectores público y privado interesados en medir variables medioambientales y de confort para promover el acceso universal al conocimiento.

Palabras clave
sistema de medición ambiental, sensores de bajo costo, calidad ambiental interior, medición de contaminantes.

# RESUMO

A saúde pública apresenta desafios multidisciplinares que envolvem uma combinação de bem-estar físico, mental e social. Duas limitações para a quantificação de poluentes internos (gases, compostos químicos e partículas em suspensão) são o alto custo e a complexidade dos sistemas de medição disponíveis. Neste cenário, uma abordagem experimental foi utilizada para desenvolver um sistema de baixo custo para medir variáveis que afetam a saúde humana e ambiental. Os processos de calibração, validação e ajuste técnico foram realizados em um local de clima extremo no sul do México, seguindo padrões nacionais e internacionais. Os principais resultados mostraram a viabilidade do uso de ferramentas de baixo custo para medir poluentes em países em desenvolvimento. 57% dos dados relativos ao H2S tiveram um resultado acima de 150 ppm, o que é considerado prejudicial à saúde humana. Por outro lado, o desenvolvimento do sistema de medição na localidade estudada mostrou a importância de contar com dados para medir os níveis de poluição ambiental de acordo com os hábitos e costumes de cada região. Foram utilizados sensores e sistemas de acesso aberto, pois podem beneficiar diretamente pesquisadores com recursos limitados e os setores público e privado interessados em medir variáveis ambientais e de conforto para promover o acesso universal ao conhecimento.

Palavras-chave:
sistema de medição ambiental, sensores de baixo custo, qualidade ambiental interna, medição de poluentes

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# INTRODUCTION

In Latin America, people spend considerable amounts of time indoors, making indoor environmental quality (IEQ) vital for health and productivity (Nilandita et al., 2019). Many of them experience poor indoor air quality, which is associated with various health issues, such as sick-building syndrome and reduced cognitive performance in educational environments (Khalil & Kamoona, 2022), and it has been seen that environmental factors contribute to between 25% and 33% of these health issues worldwide (National Institute of Public Health, 2022). Apart from this, it has been seen that exposure to sulphur dioxide ($SO_2$) can harm the airways of asthmatics (Nurhisanah & Hasyim, 2022). In this vein, Mentese et al. (2020) identified a correlation between indoor pollutants and comfort variables with respiratory symptoms, where the persistence of these indoor pollutants is influenced by climatic conditions and building characteristics (Enyoh et al., 2020). Consequently, mitigation strategies depend on the specific pollutants, construction methods, and energy policies in place. Research has highlighted the need for effective monitoring systems, indicating that indoor air can often be more polluted than outdoor air, emphasising the need for robust solutions to address these risks (Kim & Sohanchyk, 2022).

The potential for low-cost systems (LCS) to measure indoor IEQ in extreme climates in Latin America is a pressing issue. As urbanization continues to rise in Latin America, indoor air quality has become a significant concern, with implications for public health and energy efficiency. The interplay between indoor air quality (IAQ) and energy efficiency is complex, and achieving optimal IAQ often conflicts with energy-saving measures (Dabanlis et al., 2023). This is particularly relevant in extreme climates where ventilation strategies must be carefully balanced to avoid exacerbating indoor pollution levels (Tran et al., 2020). The main pollutants in the environment are divided into gases (CO, $CO_2$), chemical compounds ($CH_2O$, $NO_2$), and suspended particles (PM). When reacting with nitrogen oxides ($NO_x$), volatile organic compounds can also affect the health of the building and its users in the short and long term (Jung et al., 2021). Meanwhile, $SO_2$ and $NO_x$ are responsible for acid rain and air pollution in urban areas. On the other hand, $SO_2$ in combination with PM10 increases morbidity in chronic heart and upper respiratory patients (Secretaría de Salud, 2019). Finally, there is carbon dioxide ($CO_2$), a colourless, odourless, and tasteless gas from the complete combustion of carbon and biological respiration (Occupational Safety and Health Administration [OSHA], 2015). In summary, the potential for an LCS to measure IEQ in extreme climates in Latin America is not only a matter of public health but also a critical step towards achieving energy equity.

Jung et al. (2021) found that cost is a limitation for measuring indoor pollutants, especially in developing countries with low research resources. Although systems have been developed to measure PM and gas concentrations using development boards (Arduino, Raspberry Pi, etc.) (Kalia & Ansari, 2020), it has been shown that exposure to pollution is higher when factors such as poverty and segregation are present (Burbank et al., 2023). Health conditions have additional limitations, given the lack of information on the presence of pollutants in the indoor and outdoor environment, climate change, and other problems. García et al. (2013) studied pollution levels in Guadalajara, Mexico, and found higher concentrations of $SO_2$ after the rainy season. Mexico's diverse climates, ranging from arid to tropical, significantly affect IEQ and public health. Hence, implementing measurement systems can empower communities, especially in low-income areas, to proactively enhance their living conditions, thereby promoting energy equity and public health (Koengkan et al., 2020).

The economic situation in Mexico reinforces the need for low-cost solutions, as many households face financial constraints. Thus, developing affordable systems would promote widespread adoption, enabling communities to monitor and enhance their IEQ without significant costs (Nugroho et al., 2016). This perspective is crucial for energy equity, as low-income households often endure higher energy expenses and poorer living conditions, exacerbating health issues linked to inadequate IEQ (Balza et al., 2024). LCS could also improve understanding of the connection between indoor environmental factors and health outcomes, helping to identify pollution sources and inform public health interventions, ultimately benefiting vulnerable populations (Ginebreda & Barceló, 2022). However, in Latin American countries, the authors could not find an LCS that integrates the measurement of gases, chemical compounds, particulate matter, and thermal comfort variables in the same system. For this reason, it is important to generate new alternatives that meet domestic requirements.

The main objective was to evaluate an integral low-cost monitoring system, using current technology, and validate its technical performance in a social housing project under extreme climatic conditions in Mexico, as is the case in Merida, Yucatan, Mexico. This study will serve as a guide for environmental control in these spaces with energy poverty

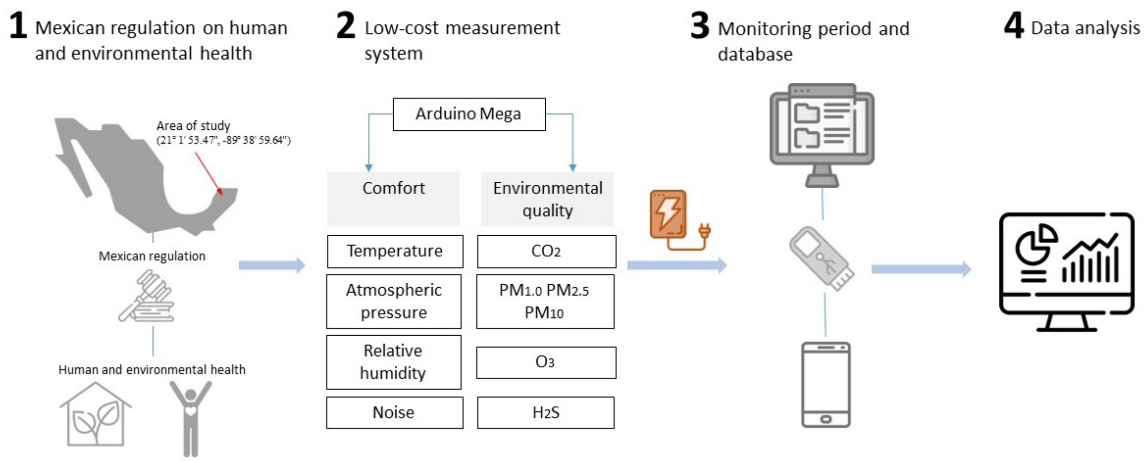


Figure 1. Methodological development for the measurement system. Source: Preparation by the authors.

Table 1. Regulatory recommendations for the main environmental pollutants. Source: Preparation by the authors.

| Pollutant | Mexican Standard | WHO (World Health Organization, 2021) | NAAQS/EPA (Environmental Protection Agency, 2022) |
|---|---|---|---|
| CO | 26 ppm (1 h) (Secretaría de Salud, 2021b) | 4 mg/m³ 4 h) | 35 ppm/h* |
| $NO_2$ | 0.106 ppm (1 h) (Secretaría de Salud, 2022a) | 25 µg/m³ (24 h) | 0.05 ppm (1 year) |
| $SO_2$ | 0.11 ppm (24 h) (Secretaría de Salud, 2019) | 40 µg/m³ (24 h) | 0.14 ppm (24 h) |
| PM | PM2.5 45 µg/m³ (24 h) | PM2.5 15 µg/m³ (24 h) | PM2.5 35 µg/m³ (24 h) |
| | PM10 75 µg/m³ (24 h) (Secretaría de Salud, 2022b) | PM10 45 µg/m³ (24 h) | PM10 150 µg/m³ (24 h) |
| $O_3$ | 0.09 ppm (1 h) (Secretaría de Salud, 2021a) | 60 µg/m³ peak season | 0.07 ppm (8 h) |
| Pb | 0.5 µg/m³ (1 year) (Secretaría de Salud, 2021c) | - | 0.15 µg/m³ ** |

* Not to exceed this concentration once a year ** 3-month average

and vulnerability. The obtained measurements were evaluated under the criteria of Mexican standards. In summary, developing LCS for measuring IEQ in Mexico is crucial not only from an economic standpoint but also for public health, energy equity, and sustainability.

# METHODOLOGY

An experimental method was employed with the following phases (Figure 1):

1. Review current environmental health regulations for buildings (domestic and international).
2. Place low-cost sensors for IEQ variables into a container with 2-inch holes on all sides to allow airflow.
3. Monitoring period and creation of a database. The location is a representative urban development in southern Mexico (Figure 1). The measuring system was placed in the entrance hall, a key point for the exchange of internal and external climatic conditions. The monitoring period considered the time it takes for all sensors to have a valid reading. The sampling rate was 20 minutes, and measurements were recorded from 09-22-2023 to 10-22-2023.
4. Analyse the results.

## ENVIRONMENTAL HEALTH REGULATIONS FOR BUILDINGS

Table 1 presents domestic and international standards establishing limits and recommendations for indoor pollutants. The Official Mexican Standard NOM-022-SSA1-2019 (Secretaría de Salud, 2019) on environmental health establishes a maximum of 0.075 ppm per hour in a 3-year arithmetic average for $SO_2$, or 0.04 ppm daily as the maximum for three consecutive

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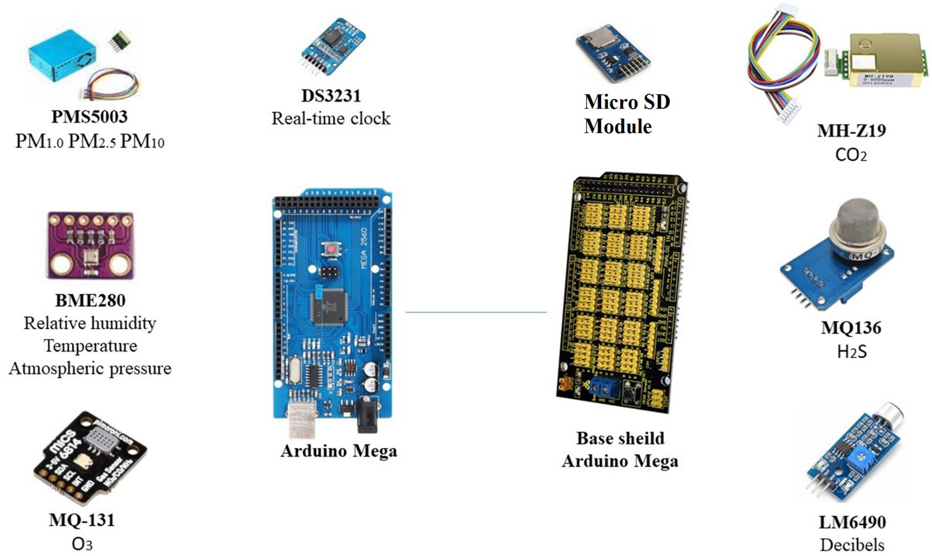


Figure 2. Diagram of sensors used in the LCS. Source: Preparation by the authors.

years. The Mexican Official Standard (Secretaría de Salud, 2022b) establishes permissible values for $PM_{10}$ and $PM_{2.5}$. $O_3$ can cause a considerable reduction in agricultural crop yields (Secretaría de Salud, 2021a). The Air Quality Guidelines (World Health Organization, 2021) are based on a global and regional assessment of diseases caused by air pollution. These levels are not mandatory, but are considered a reference for IEQ. Table 1 summarises the pollutant concentration recommendations of the Mexican and international standards.

$CO_2$ levels indicate air quality because an excess of this chemical compound can become an asphyxiant gas. ASHRAE (2024) suggests that indoor $CO_2$ levels should not exceed 1000 ppm (ASHRAE, 2024; Gangwar et al., 2024). Meanwhile, the Occupational Safety and Health Administration sets a limit of 5000 ppm in 8 h and 2 ppm every 15 minutes for formaldehyde (OSHA, 2015). In Mexico, maximum concentration limits have been established for the following pollutants in ambient air: ozone, carbon monoxide, sulphur dioxide, nitrogen dioxide, lead, total suspended particles, and suspended particles smaller than 10 and 2.5 micrometres (Secretaría de Salud, 2021a).

## LOW-COST SYSTEM DEVELOPMENT

The development of the prototype considered the stages described below.

- System selection. The selection and procurement are based on regional custom analysis and market availability to measure IEQ variables such as gases, chemical constituents, PM, and noise levels.
- Calibration.
- Adjustments and validation.
- Analysis of results.

Figure 2 shows the measurement system's sensors and components. LCS reduced the cost of commercial measurement equipment for recording the same environmental variables by approximately 85 %, resulting in a total cost of USD 350.

## CALIBRATION

The calibration consisted of setting the measurement system for a house in southern Mexico, coordinates (21° 1′ 53.47″, -89° 38′ 59.64″). The location experiences an average annual temperature of 33.6 °C (Sistema Meteorológico Nacional, 2020). It has a typical yearly relative humidity of 73% and an annual solar irradiance averaging 233.5 W/m² (Red Universitaria de Observatorios Atmosféricos, 2023). The extreme thermal characteristics of the locality determined the interest in this site. Commercial monitoring equipment with calibration certificates was used to validate the LCS sensors' measurements. This section presents the calibration of the relative humidity variable as an example. The procedure described was very similar and, in many cases, the same as that used for all variables measured by the LCS. First, the low-cost BME280 sensor, capable of providing temperature, relative humidity, and atmospheric pressure measurements, was connected to the open-source Arduino Mega development board and configured to take relative humidity readings every 10 seconds. The average of these readings was stored every 5 minutes. The sampling rate was selected to match the configuration of the HOBO U12-012 data

Table 2. LCS (BME280) and reference instrument (HOBO U12-012). Source: Preparation by the authors.

| Sensor | Brand | Measuring range | Accuracy | Resolution |
|---|---|---|---|---|
| BME280 | BOSCH | 0 – 100 % | ±3% | 0.008 % |
| HOBO U12-012 | Onset | 5 – 95 % | ±2.5% | 0.05 % |

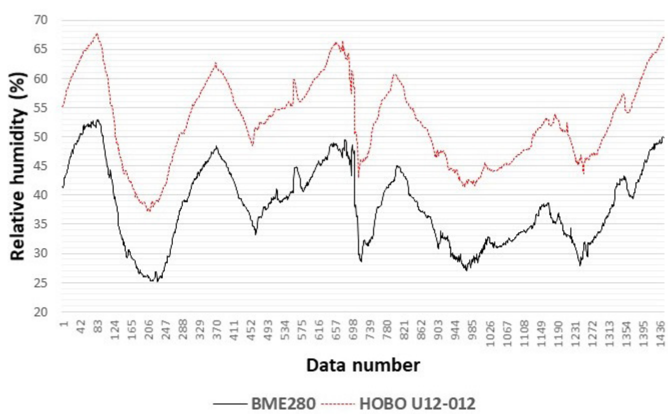


Figure 3. Relative humidity measurements under LCS and the reference instrument. Source: Preparation by the authors.

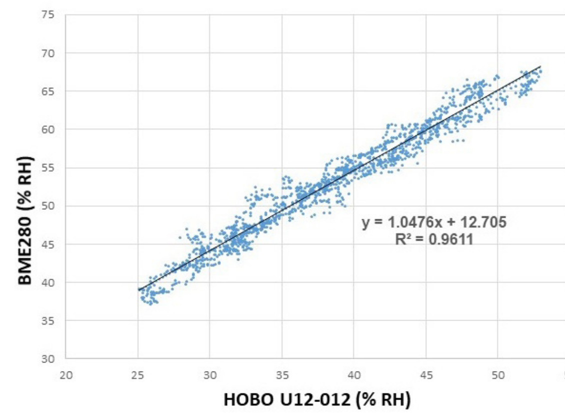


Figure 4. Least squares linear regression plot of the LCS and the reference. Source: Preparation by the authors.

acquisition system used as the reference instrument for calibration. The main characteristics of the LCS and the reference instrument are shown in Table 2.

The calibration process was performed using the "Calibrated Reference" method (Nicholas J. V. & White D. R., 2001). This method consists of comparing measurements of the device being tested (DTU) against the measurements of a calibrated instrument, which must be certified, and its calibration must be traceable to domestic and international standards. Thus, both instruments are placed in a room under equal conditions and left to measure simultaneously. Once the measurement period was over, which in this case was a little more than five days, the data stored in the memory of each device were collected and analysed in a statistical sheet. 1445 sampled data pairs were plotted against time to see if they were acquired correctly (Figure 3).

Figure 3 shows that the DTU measurements are consistently below those of the reference instruments, representing an approximate -12.7 (% RH) offset. The data was fitted into a scatter plot for linear least squares regression. A fitting equation was obtained using this linear regression that minimised the sensitivity (slope) and offset errors (Figure 4).

## ADJUSTMENTS AND VALIDATION

The correction equation was obtained from the calibration described in section 2.3 :

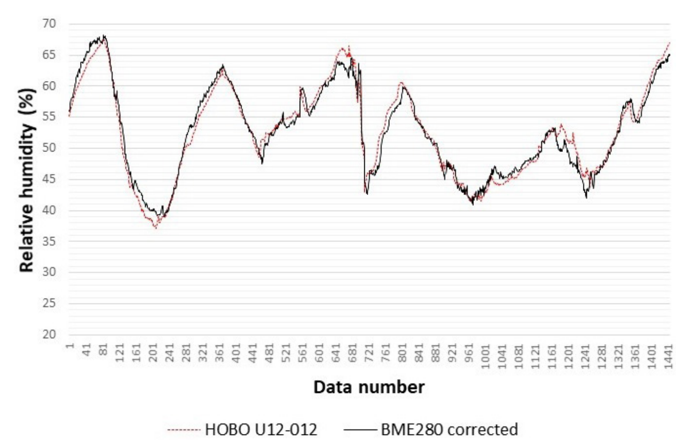


Figure 5. Comparison of BME280 against HOBO U12-012. Source: Preparation by the authors.

$$y = 1.0476x + 12.705$$

Where  is the Relative Humidity (calibrated) in percentage and  is the Relative Humidity measurement reported by the BME280 sensor. The last term of equation (1) is the offset compensation of the low-cost sensor measurements. Equation (1) was applied to the data from the LCS BME280 to reduce the error concerning the commercial sensor HOBO U12-012 measurements. The corrected data, together with the reference sensor data, can be seen in the graph of Figure 5. From this graph, the calibrated measurements match the behaviour and magnitude of the reference instrument.

Potential of a low-cost system for measuring indoor environmental quality in Latin American extreme climates towards energy equity
Claudia Eréndira Vázquez-Torres, Renán Gabriel Quijano-Cetina, Israel Sánchez-Domínguez, Bassam Ali
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At the end of the functional testing, calibration, and validation, the code of the sensors was shared to promote universal access to knowledge and to provide continuous feedback to improve the system through the following link: https://shorturl.at/Nzn1g

## RESULTS AND DISCUSSION

2232 results were obtained for each variable measured from September 22nd to October 22nd, 2023. Figure 6 and Figure 7 present the hourly averages during the monitoring period. The dotted red lines represent the upper limit of the comfort model (CM) for relative humidity, air temperature, and the regulatory limits for pollutants ($O_3$, Particulate Matter, $CO_2$, $H_2S$, and decibels). Figure 6a presents the temperature behaviour with the adaptive CM of the ASHRAE Standard 55, which satisfies 80% of the users (Quah, 2021). During the measurement period, there were no heating needs, so it was not necessary to represent the lower limit of the CM. This was similar for relative humidity, whose behaviour is presented in Figure 6b with the upper limit of the CM (between 30% and 50 %). 85% of the monitoring time presented cooling needs under an adaptive CM to satisfy 80% of the users, and 74% of the data were observed above the CM for relative humidity. Figure 6c presents the results for the noise level. NOM-081-SEMARNAT-1994 (Secretaría de Medio Ambiente y Recursos Naturales, 2024) establishes noise limits of 55 dB.

Figure 7a does not show the regulatory limit of NOM-020-SSA1-2021 (Secretaría de Salud, 2021a) because it is 0.09 ppm per hour, and no values above this were present during the monitoring period. The red line in Figure 7b represents the WHO limit for $PM_{2.5}$. There were no values above the limits recommended by Mexican regulations (45 and 75 microns for $PM_{2.5}$ and $PM_{10}$, respectively). 3.6 % of $PM_{2.5}$ was observed above the WHO regulatory limit. It is important to note that $PM_{1.0}$ has no regulatory exposure limit. The regulatory limit of 500 ppm for $CO_2$ in Figure 7c was set for outdoor spaces, which is representative of this study because there are no regulations to qualify indoor spaces (ASHRAE, 2024).

The Occupational Safety and Health Administration [OSHA] (2024) states that 100 ppm $H_2S$ for more than 1 hour could generate irritation; between 100 ppm and 150 ppm would produce the risk of fatigue or olfactory paralysis and increase the risk by increasing the hours of exposure to this gas. In the monitoring period, values above 150 ppm could risk human health (Figure 7d). The case

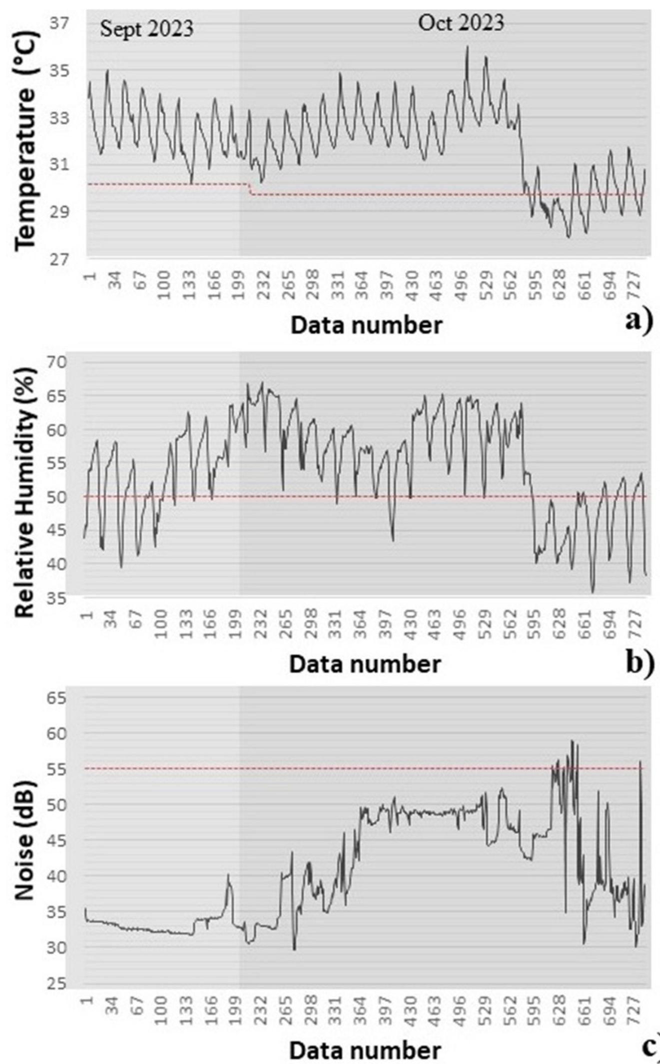


Figure 6. Results of the monitoring period for comfort variables.
Source: Preparation by the authors.

study allowed the design of a monitoring system that reduced the cost of commercial sensors for measuring environmental quality and comfort variables by 85 %. Afroz et al. (2023) emphasised the importance of calibrating and validating low-cost sensors. The authors documented the possible influence of relative humidity on sensors measuring PM2.5 when RH is above 75 % due to excess ambient water. On the other hand, Cowell et al. (2022) monitored particulate matter, temperature, and relative humidity in a residential environment using sensors for less than USD 126. These authors agreed on the influence that excess humidity could have on the accuracy of the sensors. Meanwhile, Frederickson et al. (2023) measured $NO_2$, $O_3$, and $PM_{2.5}$ and used a linear regression model to calibrate low-cost sensors. In this study, RH was below the limits detected as harmful for LCS. Tang

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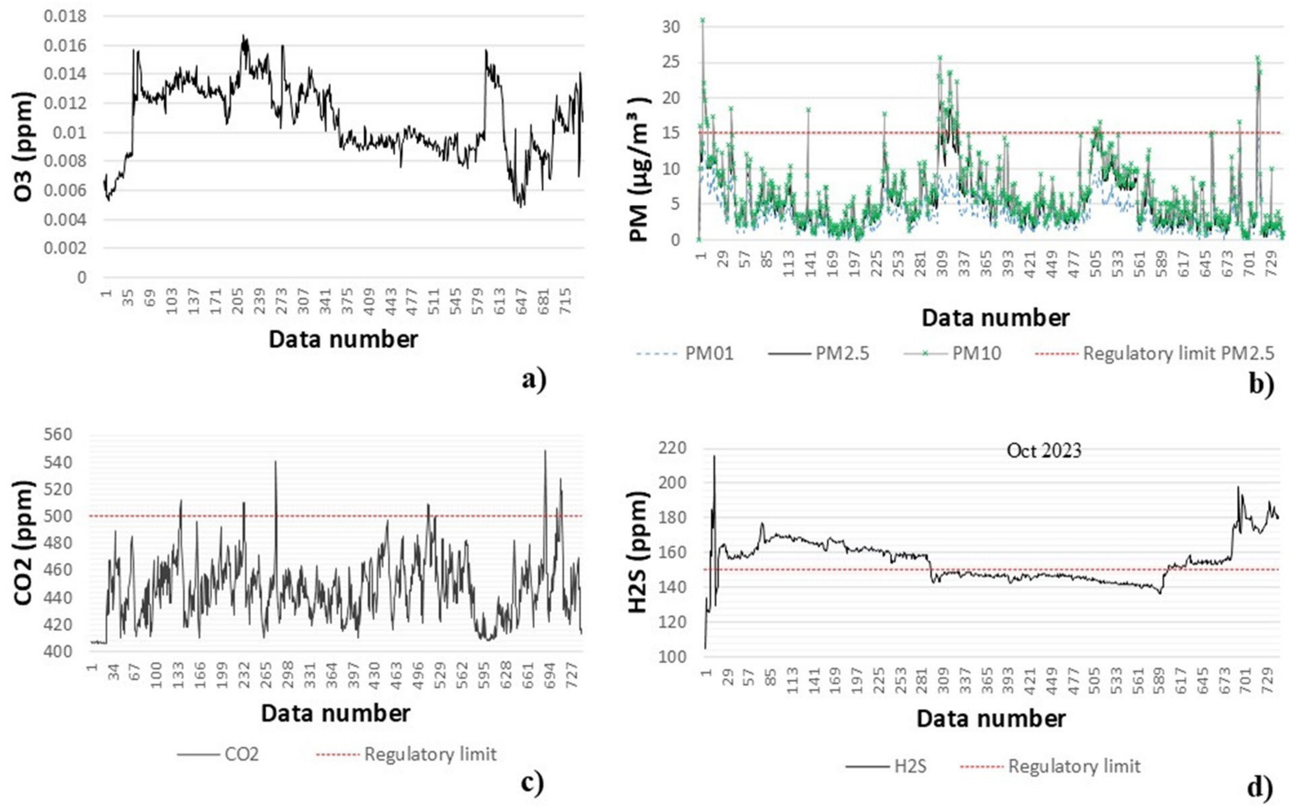


Figure 7. Results of the monitoring period for IEQ variables (pollutants). Source: Preparation by the authors.

and Pfrang (2023) used a linear regression method as a calibration method for low-cost sensors to measure suspended particles, with an overall accuracy of 70.7 %. These authors, in this case, recommended periodic calibrations and comparing LCS with high-accuracy instruments where possible, criteria that matched the characteristics of this study.

Ortiz et al. (2022) designed an experimental system to measure Mexico's temperature, relative humidity, and air speed. They compared their data against numerical data and found a maximum difference of almost half a degree Celsius. These findings show the interest in generating adequate instrumentation to address climate change in Latin America. Although Mexico's National Air Quality Information System generates real-time information through continuous monitoring stations (Ministry of Environment and Natural Resources, 2024), there are localities in the south with only one station and gaps in the information from recent years. The results represent a long-term challenge to corroborate the optimal functioning of the sensors in their performance and as an integral system. To this end, a calibration process should be periodically carried out to detect possible errors promptly.

As an area of opportunity, extending the monitoring period to one year and comparing the results with monitoring station databases as a reference is necessary to ensure the optimal functioning of the LCS. In the next stage, it is proposed that the LCS be located in other sectors and geographical locations to extend the range of influence and the available database. Additionally, the LCS performance is limited by the accuracy of the reference instrument used during calibration. Finally, historical data measured with reliable instrumentation represent a greater certainty about the presence of pollutants in the residential sector in Mexico. The results put into perspective two possible routes for localities in Latin America. The first is aimed at stakeholders, who could generate effective strategies to improve users' quality of life in the face of sudden climate change. The second refers to the environmental education needed in Latin American countries, with dissemination and outreach events backed by accurate data to inform the population and generate awareness towards informed adaptation to climate change.

## CONCLUSIONS

This study developed an LCS for measuring environmental quality variables in buildings, validating and calibrating the sensors at a site in southern Mexico. The results demonstrated an 85% saving compared to off-the-shelf measuring systems, thereby enabling universal access to the instrumentation and, consequently, to knowledge regarding the reduction of indoor pollution in homes.

The implementation of the proposed LCS may be particularly beneficial for developing countries such as Mexico. The measurements taken over a month revealed that the thermal characteristics of the study locality align with those of an extreme climate, highlighting the need for cooling, even in a month that is not the warmest. This highlights the importance of periodically monitoring residential spaces to ensure compliance with Mexican regulations, which still require updates to address pollutants that lack specific regulatory limits and pose a risk to public health.

The results from the measurement month, between September and October 2023, indicated that the regulatory limits for several pollutants were exceeded, reinforcing the need for continuous monitoring. The LCS developed in this study presents itself as a potential tool for addressing the challenges of climate change with a focus on social equity by providing data that can guide strategies to reduce emissions from pollutant sources within homes. This approach not only contributes to improving IEQ but also promotes energy equity in Mexico, ensuring that all communities have access to the necessary resources for a healthier living environment. However, the accuracy of the developed LCS can be improved if a calibrated reference instrument with a higher accuracy level becomes available.

# AUTHOR CONTRIBUTIONS CRediT

Conceptualization, R.G.Q.C., C.E.V.T.; Data Curation, R.G.Q.C., C.E.V.T.; Formal Analysis, R.G.Q.C., C.E.V.T.; Funding Acquisition; Research, C.E.V.T.; Methodology, C.E.V.T., R.G.Q.C.; Project Management, I.S.D., A.B.; Resources, R.G.Q.C., C.E.V.T., I.S.D., A.B.; Software, R.G.Q.C.; Supervision, I.S.D., A.B.; Validation, R.G.Q.C.; Visualization, R.G.Q.C., C.E.V.T.; Writing - original draft, C.E.V.T.; Writing - revision and editing, R.G.Q.C.

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