

Drone–IoT System for Low-Cost Intelligent Monitoring of Atmospheric Pollution in Industrial and Urban Environments

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Abstract

This article presents the development and implementation of an intelligent atmospheric monitoring system based on UAV and IoT technology, as an alternative to the traditional static stations used in industrial environments. The proposal integrates a drone equipped with environmental sensors for the measurement of temperature, pressure, humidity, particulate matter (PM), gas, and CO₂, together with an IoT architecture based on a Raspberry Pi 5 that enables data acquisition, storage in an SQL database, and real-time visualization through a dashboard accessible on the local network. The modular design of the system facilitates its scalability and the possible future integration of multiple drones to increase the spatial and temporal density of sampling. During November and December 2025, two daily flights of approximately 15 minutes were carried out, generating a dataset that made it possible to analyze the temporal behavior of the meteorological and pollutant variables. The results show that atmospheric conditions directly influence the dispersion and variability of pollutants, with significant fluctuations observed in dust and gases, while CO₂ exhibited greater stability as a background indicator. The findings demonstrate that dynamic UAV-based monitoring offers greater flexibility, spatial coverage, and the ability to detect isolated episodes compared with fixed systems, establishing itself as an efficient, low-cost technological solution with high potential for application in industrial environmental management and regulatory compliance.

Keywords

UAV, IoT, air quality monitoring, drone, environmental management.

1. Introduction

This article was initiated at the University of Lima (Peru), where the UAV prototype was developed and the sensors were integrated, and was completed at the Autonomous University of Nuevo León (Mexico), where the data-acquisition architecture and the experimental tests were carried out. At present, atmospheric pollution mapping in industrial companies is performed by means of static stations, which can be described as a fixed, autonomous installation designed to continuously measure environmental pollution. Although these are essential for emission

control, they face challenges arising from climatic variables that affect the accuracy of the data collected; factors such as wind speed, temperature, and atmospheric humidity interfere with the dispersion of pollutants, producing results susceptible to inaccuracies.

The purpose of the project is to carry out comprehensive atmospheric monitoring using UAV technology in order to determine, accurately and in detail, the main pollutants present in the environment. This proposal seeks not only to identify and quantify the emissions generated by industrial activities, but also to provide data for environmental assessment, the prevention of potential pollutants, the protection of public health, and the efficient management of industry. Through the strategic use of drones, the aim is to achieve detailed spatial coverage and real-time data collection, which will make it possible not only to comply with current national and international regulatory standards, but also to establish a solid basis for the design of more effective environmental policies and the development of responsible and sustainable industrial practices. Ultimately, this project aspires to contribute to environmental well-being, promoting more conscious industrial management committed to the preservation of the environment and the health of the community.

1.1 Main Objective

- To design and build a prototype unmanned aerial vehicle (UAV) integrated with specialized sensors for the measurement and monitoring of atmospheric pollutants.

1.2 Specific Objectives

- To carry out experimental tests of atmospheric pollutant measurement with the UAV prototype in controlled environments.
- To validate the proposed system, assess its operational feasibility, and identify the scope and limitations of the study.
- To propose an alternative strategy for the control and mitigation of atmospheric pollution applicable to industrial environments.

2. Literature Review

Atmospheric pollution monitoring has traditionally relied on fixed measurement stations, widely used by government agencies and companies to assess air quality. These systems provide pollution mapping from a single fixed point, which leads to various limitations in their accuracy; in addition, their installation, maintenance, and operation entail high costs. In recent years, the development of unmanned aerial vehicles (UAVs) equipped with environmental sensors has emerged as a low-cost, flexible, and adaptable alternative for mapping atmospheric pollutants. This section reviews the main advances in the use of drones for environmental monitoring, as well as their advantages, limitations, and technical challenges.

While networks of fixed stations have been the backbone of official air-quality monitoring systems, their high installation and maintenance cost limits their spatial density and, consequently, their ability to detect local variations in pollution. In response to this limitation, recent literature has highlighted the importance of alternative technologies that combine unmanned aerial vehicles (UAVs) with low-cost environmental sensors to obtain data with greater spatial and temporal resolution.

Several studies have indicated that low-cost sensors (LCS), such as electrochemical, MOS, and optical sensors for particulate matter, can be effectively integrated into mobile platforms to measure gases and environmental variables such as CO₂, temperature, and relative humidity, significantly reducing costs compared with traditional stations (Narayana et al. 2022). This cost reduction makes it possible to expand the spatial coverage of monitoring, especially in areas where fixed infrastructure is limited or nonexistent.

In recent years, several studies have examined the technical feasibility of UAVs as atmospheric monitoring platforms. Experimental work shows that multirotor drones can carry particulate-matter and gas sensors while maintaining flight stability and real-time transmission, enabling emission-source identification and three-dimensional pollution mapping (Suchanek et al. 2023). Platforms with sensor-lifting or sensor-separation mechanisms have also been proposed to reduce propeller-induced aerodynamic interference and improve measurement accuracy (Szczurek et al. 2023). In specific applications, the usefulness of UAVs equipped with environmental sensors has been demonstrated for the geospatial analysis of pollutants in real environments, such as landfills and urban areas with a high pollutant load,

showing that these platforms can effectively complement traditional fixed stations (Ranganathan et al. 2023). These studies agree that UAVs allow greater operational flexibility, access to hard-to-reach areas, and vertical sampling capability, which represents a significant advantage over static systems.

Nevertheless, the literature also identifies important technical challenges. These include the need for periodic calibration of low-cost sensors, the influence of environmental factors on measurement stability, and the effect of the turbulent flow generated by the drone's rotors (Szczurek et al. 2023). Although LCS present limitations compared with reference analyzers, their proper calibration and validation make it possible to obtain reliable results for exploratory monitoring and spatial-mapping applications.

Overall, the scientific evidence suggests that the integration of UAVs with low-cost environmental sensors constitutes a technically and economically viable alternative for mapping atmospheric pollution. This trend reflects a shift toward more flexible, scalable, and accessible monitoring systems, capable of complementing traditional networks and improving the spatial characterization of pollutants.

3. Methods

3.1 Aerial Platform and Prototype Fabrication

The prototype is based on the commercial F450 quadcopter, which offers a suitable balance between robustness, maneuverability, and customization for environmental monitoring systems. From this base, a modular design was adopted to ease sensor integration, maintenance, and reconfiguration. Custom structural components—sensor mounts, electronic compartments, vibration-minimizing fastening systems, and a battery housing—were developed through three-dimensional modeling in Autodesk Fusion 360 and Autodesk Inventor (Figure 1). The designed parts were 3D-printed, reducing costs, accelerating design iterations, and adapting the geometry to the sensor system's requirements. This rapid prototyping enabled progressive validation of the mechanical design and its adjustment to the aerodynamic behavior and mass distribution. The flight control system was implemented using an APM 2.8 controller, configured for autonomous missions and geo-referenced data collection, through the Mission Planner APM 2.0 software.

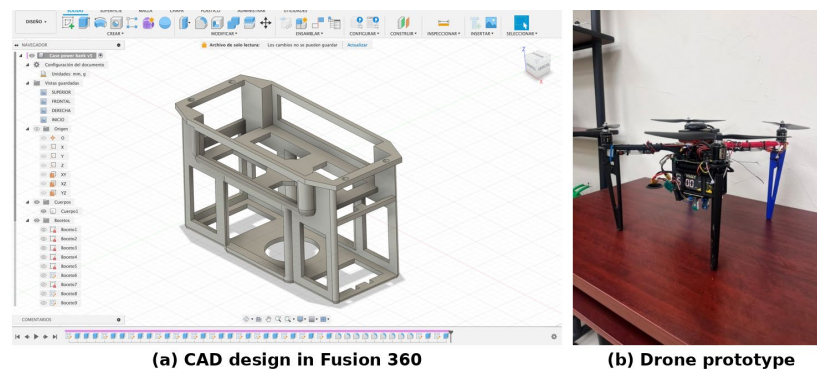


Figure 1. (a) CAD design in Fusion 360 and (b) drone prototype.

3.2 Environmental Sensor System

The implemented sensor set includes:

- MH-Z19B carbon dioxide sensor, with a selectable measurement range of 0–2000/5000/10000 ppm and an accuracy of $\pm(50 \text{ ppm} + 5\% \text{ of the reading})$.
- Sharp GP2Y1010AU0F particulate-matter sensor, with a measurement range of 0–600 $\mu\text{g}/\text{m}^3$.
- DHT22 relative-humidity and temperature sensor, operating over a temperature range of -40°C to $+80^\circ\text{C}$ and a relative humidity of 0–100%; it also has an accuracy of $\pm 0.5^\circ\text{C}$ for temperature and $\pm 2\%$ for relative humidity.
- BME280 sensor, used for measuring atmospheric pressure, temperature, and humidity, operating over a temperature range of -40°C to $+85^\circ\text{C}$, relative humidity of 0–100%, and pressure of 300–1100 hPa; it also has a resolution of $\pm 0.01^\circ\text{C}$ for temperature, $\pm 3\%$ for relative humidity, and 0.16 hPa for pressure.

- MQ-2 combustible-gas sensor, non-selectively sensitive to flammable gases such as LPG, propane, methane, hydrogen, and smoke (it does not specifically measure carbon monoxide), with a detection range of 100–10,000 ppm and an analog output digitized at a resolution of 10 bits.

The integration of these sensors makes it possible to obtain instantaneous geo-referenced atmospheric measurements during flight. The electronic architecture, supported by a custom PCB, facilitates stable power distribution, signal organization (UART, I2C, and digital), and the reduction of electromagnetic interference generated by the drone's motors.

Prior to the flight tests, a functional verification of the sensors was carried out in controlled spaces to confirm their correct operation and rule out defective units, since they are low-cost commercial devices. Each sensor was exposed to known reference conditions—for example, a closed, stable environment for CO₂ and relative humidity, and clean air for particulate matter—and its readings were compared with the values expected from each device's datasheet. The sampling frequency, set by the reading cycle configured in Node-RED, was one sample every 10 seconds (six samples per minute). It should be noted that this verification is not a traceable calibration against certified reference instruments; therefore, the data must be interpreted in relative terms, as detailed in the Study Limitations section.

3.3 Electronic Integration and PCB Design

To optimize the interconnection between the environmental sensors and the processing unit, a custom printed circuit board (PCB) was designed in Autodesk Eagle (Figure 2). It centralizes the power supply, stabilizes signals, reduces electrical interference, improves cable organization, and minimizes loose or unstable connections during flight, while facilitating the link to the Raspberry Pi. A Raspberry Pi served as the main processing unit for the acquisition, storage, and preliminary management of the sensor data. The electronic architecture was conceived to ensure compatibility between analog and digital sensors and to allow future expansions without a complete redesign. This custom electronic-integration approach constitutes a key element of the project's added value, as it enables an open, scalable architecture that is adaptable to different environmental-monitoring configurations.

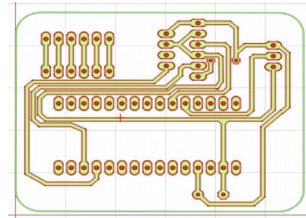


Figure 2. PCB design in Autodesk EAGLE

3.4 Sensing System and Flight Protocol

The sensing system was designed to perform geo-referenced atmospheric measurements through controlled flights over previously defined locations within the study area. The sampling strategy was structured under a stationary, point-based scheme, making it possible to record instantaneous pollutant concentrations at specific positions with a controlled dwell time.

Five sampling points were established, strategically distributed across the evaluated area. The geographic coordinates of each point were as follows:

- **P1: Latitude 25.7266481°, Longitude –100.3144830°**
- **P2: Latitude 25.7266456°, Longitude –100.3140807°**
- **P3: Latitude 25.7273391°, Longitude –100.3141129°**
- **P4: Latitude 25.7273295°, Longitude –100.3144991°**
- **P5: Latitude 25.7269815°, Longitude –100.3143114°**

The system was operated under a teleoperated scheme using a Futaba 12K radio control, allowing direct supervision throughout the mission. The drone operated in Loiter flight mode, which uses GPS assistance to maintain a stable position over each sampling point, reducing unwanted horizontal displacements during data acquisition. The operating altitude was 5 meters above ground level, kept constant during each mission in order to ensure uniformity in the

measurement conditions. At each point, the drone remained stationary for 2 minutes, continuously recording data through the integrated sensor system. The type of sampling implemented was stationary, allowing local concentrations to be captured with minimal spatial variability during the acquisition period. The displacements between sampling points were carried out at a low horizontal speed; the transit speed used was less than 4 m/s, in order to minimize the disturbance of the airflow around the sensors; during the dwell at each point, in Loiter mode, the horizontal speed of the drone was practically zero.

Two daily flights were carried out, each lasting approximately 15 minutes: one in the morning and another in the afternoon (Figure 3). This strategy made it possible to assess possible intraday variations in the concentrations of atmospheric pollutants, associated with changes in anthropogenic activity and environmental conditions.



Figure 3. Prototype flight.

3.5 IoT Architecture and Information Management

The IoT data-management architecture was designed to acquire, store, and visualize the atmospheric measurements in real time during the flight missions. It was implemented on a Raspberry Pi 5, which acted as the central unit for reading the sensors, preprocessing the data, and transmitting them to the storage server. The acquisition logic was programmed in Node-RED with structured workflows for the periodic reading of each device. Within its visual, node-based environment, Node-RED integrated the communication protocols (UART, I2C, and digital GPIO), enabling the temporal synchronization of the measurements and the uniform structuring of the records (Figure 4)

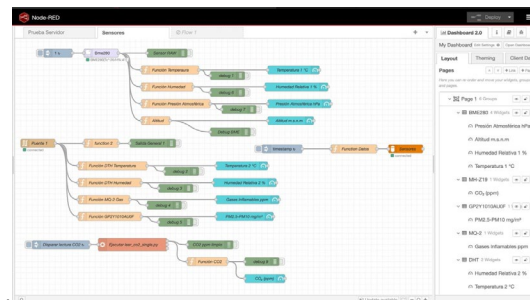


Figure 4. Programming in Node-RED

The acquired data were sent to a relational database programmed in SQL, hosted on a server with an Apache environment. This client-server architecture made it possible to separate field processing from centralized storage, improving the robustness of the system and ensuring the persistence of the collected information. The database schema was designed to store geographic coordinates (latitude and longitude), timestamp, CO₂ concentrations, particulate-matter values, temperature, relative humidity, and atmospheric pressure. In addition to structured storage, the integration of Node-RED enabled the implementation of a dashboard, which made it possible to monitor the environmental variables in real time during the flight. This panel included graphical visualization of temporal trends, instantaneous numerical indicators, and online validation of the sensor system's operation (Figure 5).

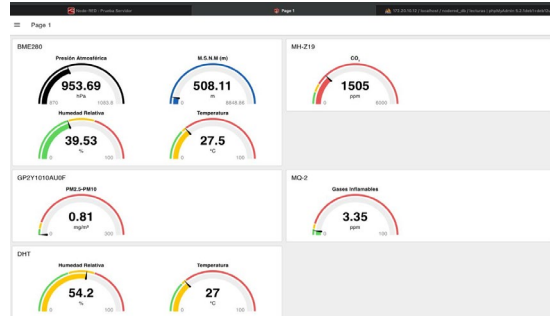


Figure 5. Dashboard

The real-time monitoring capability represented a significant operational advantage, as it made it possible to verify the stability of the measurements during the mission and to detect possible technical anomalies immediately. Likewise, the implemented architecture facilitates the future scalability of the system toward continuous remote-monitoring schemes or integration with analysis platforms.

3.6 Monitoring System Connections

The monitoring system on board the drone integrates the connected sensors at two data-acquisition levels, which transmit their signals to the microcontroller, which processes and centralizes the information before sending it to the Raspberry Pi 5. The latter also directly receives the readings from the MH-Z19 and BME280 sensors (Figure 6).

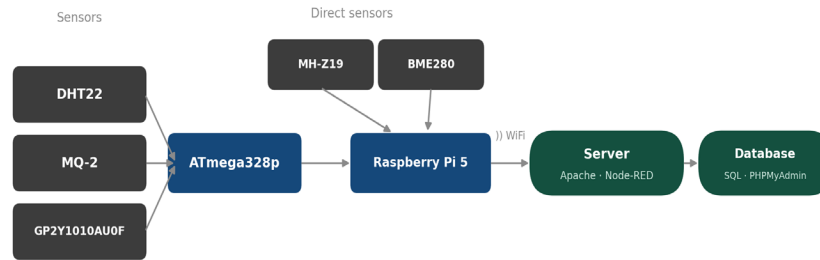


Figure 6. Wiring diagram of the atmospheric monitoring system

Once the Raspberry Pi 5 consolidates all the readings, it transmits them wirelessly via WiFi to the server, where Apache and Node-RED manage the reception and flow of the data. After that, the data are stored in an SQL database, allowing their subsequent query, visualization, and analysis for air-quality mapping.

4. Discussion and Results

4.1 Maximum Permissible Limits

The flight tests and measurements were carried out at the Autonomous University of Nuevo León (Mexico). For interpreting the data, Mexican environmental regulations (NOM) were prioritized, complemented by the World Health Organization air-quality guidelines (WHO 2021) for CO₂ and humidity, for which no NOM values were available. Table 1 presents the maximum permissible limits and guideline values for PM_{2.5}, PM₁₀, TSP, smoke, CO₂, and humidity, which constitute the technical basis for the environmental-compliance analysis.

Table 1. Maximum Permissible Limits of pollutants according to the NOM and the WHO

Pollutant	Limit in Mexico (NOM)	Standard	WHO Limit	Scope
PM _{2.5} (outdoor air)	45 µg/m ³ / 24h	NOM-025	15 µg/m ³	Public health
PM ₁₀ (outdoor air)	75 µg/m ³ / 24h	NOM-025	45 µg/m ³	Public health
TSP (LP/NG gas stacks)	50 000 µg/m ³	NOM-085	—	Industrial emissions
TSP (diesel / fuel oil)	230 000 µg/m ³	NOM-085	—	Industrial emissions

TSP (coal)	400 000 $\mu\text{g}/\text{m}^3$	NOM-085	—	Industrial emissions
Smoke (opacity)	Ringelmann 1–2	NOM-086	—	Visual control
CO ₂	Not regulated	—	400–600 ppm (natural)	Outdoor
Humidity	Not regulated	—	40–60% (recommended)	Environmental condition

It is necessary to distinguish the nature of each reference value: the NOM standards (NOM-025, NOM-085, and NOM-086) are mandatory in Mexico, whereas the WHO values are non-binding recommended guidelines. Moreover, the total suspended particulate (TSP) limits of NOM-085 are defined for fixed-source emissions (stacks) and are not directly comparable with the PM_{2.5} and PM₁₀ limits of NOM-025, established for ambient air; therefore, they are used only as an indicative reference and not as a formal regulatory-compliance criterion. The regulatory values were also used to define operating ranges compatible with the on-board instrumentation. Particulate matter was measured with a low-cost optical sensor that estimates mass concentration (PM dust) in $\mu\text{g}/\text{m}^3$; although suitable for mobile, spatial-mapping applications, it has limited absolute accuracy compared with certified gravimetric methods. For internal consistency, particulate-matter concentrations are reported in $\mu\text{g}/\text{m}^3$ throughout the analysis (Tables 2 to 4 and the corresponding figures), allowing direct comparison with the limits in Table 1.

Accordingly, the signal was treated as a representative indicator of PM_{2.5} and PM₁₀ levels, applying a linear adjustment for consistency with the regulatory ranges and with the levels typically reported in the urban-industrial context of Nuevo León. The results must therefore be interpreted in terms of relative compliance and possible exceedance of the permissible limits rather than as official gravimetric measurements. Finally, CO₂ and humidity complement the analysis by contextualizing the emission and atmospheric-dispersion conditions during the flights.

4.2 Statistical Analysis

Air-quality monitoring by means of drones represents an efficient and flexible alternative to traditional stationary measurement methods. During the flight tests carried out, the drone acquired a total of 3,610 continuous raw readings. After data cleaning —removal of negative values and of zeros associated with sensor initialization or communication errors— and the retention of the geo-referenced readings at the sampling points, the final dataset of 832 samples was formed, on which the statistical analyses presented in this section were performed. This dataset simultaneously captures meteorological variables (temperature, relative humidity, atmospheric pressure, and altitude) and pollutant concentrations (combustible gas, particulate matter, and CO₂). The descriptive statistical results of the final dataset are presented below.

Table 2. Descriptive statistics of the meteorological and atmospheric-pollution variables

Variable	Valid n	Mean	SD	Minimum	Maximum	95% CI Lower	95% CI Upper
Temperature (°C)	832	25.29	3.39	19.32	34.19	25.06	25.52
Humidity (%)	832	40.91	12.06	15.68	63.69	40.09	41.73
Pressure (hPa)	832	955.56	1.94	952.78	959.04	955.43	955.69
Altitude (m)	832	491.76	16.96	461.43	516.08	490.61	492.91
Combustible gas (ppm)	832	1.40	0.83	0.00	4.97	1.34	1.46
Dust (PM, $\mu\text{g}/\text{m}^3$)	832	512.84	416.36	0.00	1310	484.54	541.13
CO ₂ (ppm)	832	911.74	499.86	401.00	2652.00	877.77	945.71

Note. SD = Standard Deviation; 95% CI = 95% Confidence Interval. The statistics were computed on the final set of 832 geo-referenced samples; negative particulate-matter values (optical-sensor noise and baseline drift) were clipped to zero before the analysis.

The descriptive data reveal heterogeneous environmental conditions throughout the measurement days. Temperature ranged between 19.32 °C and 34.19 °C, with a mean of 25.29 °C (SD = 3.39) and a 95% confidence interval between 25.06 °C and 25.52 °C, consistent with warm daytime conditions in the study area. Relative humidity had a mean of 40.91% (SD = 12.06), while atmospheric pressure remained stable at around 955.56 hPa (SD = 1.94). Among the pollutants, CO₂ showed the greatest variability: its mean reached 911.74 ppm (SD = 499.86), with a skewed distribution reflecting episodes of elevated levels, possibly associated with limited ventilation or proximity to emission sources. Dust (PM) recorded a mean of 512.84 $\mu\text{g}/\text{m}^3$ (SD = 416.36), and the combustible gas measured by the MQ-

2 sensor showed a mean of 1.40 ppm (SD = 0.83), a value that provides a qualitative indication of the presence of combustible gases. All statistics were computed on the final set of 832 geo-referenced samples.

In order to identify relationships between meteorological conditions and pollutant concentration, Pearson correlation coefficients were computed for each pair of variables. The results are summarized in Table 3

Table 3. Pearson correlation matrix between meteorological variables and atmospheric pollutants

Meteorological Variable	Combustible gas (ppm)	Dust (PM, $\mu\text{g}/\text{m}^3$)	CO ₂ (ppm)
Temperature (°C)	0.013ns	-0.401	-0.224
Humidity (%)	0.009ns	0.399	0.217
Pressure (hPa)	-0.058	-0.316	-0.176
Altitude (m)	0.058	0.317	0.176

Note. Pearson correlation coefficients (r). Negative values indicate an inverse relationship between variables.

The correlation matrix shows that temperature is the meteorological variable most strongly associated with the pollutants: it is inversely related to dust ($r = -0.401$, $p < 0.001$) and CO₂ ($r = -0.224$, $p < 0.001$), which suggests that heat favors the vertical dispersion of these pollutants. Humidity, by contrast, shows positive correlations with both ($r = 0.399$ and $r = 0.217$, respectively), indicating that more humid conditions coincide with higher concentrations at the sensor level. Pressure and altitude show patterns opposite to each other, with moderate but statistically significant magnitudes. Gas shows no significant correlation with temperature or humidity, which points to its concentration responding to point sources rather than to general meteorological conditions. In addition to exploring the relationships between variables, it is necessary to determine whether the differences observed between flight days are statistically significant. To this end, the Kruskal-Wallis test was applied, the results of which are presented in Table 4.

Table 4. Results of the Kruskal-Wallis test for differences between flight days

Variable	H (Kruskal-Wallis)	gl	Significance
Temperature (°C)	2396.435	11	$p < 0.001$
Humidity (%)	2890.691	11	$p < 0.001$
Pressure (hPa)	2036.993	11	$p < 0.001$
Altitude (m)	2037.182	11	$p < 0.001$
Combustible gas (ppm)	2315.406	11	$p < 0.001$
Dust (PM, $\mu\text{g}/\text{m}^3$)	1544.932	8	$p < 0.001$
CO ₂ (ppm)	1078.306	8	$p < 0.001$

Note. H = Kruskal-Wallis statistic; df = degrees of freedom (number of days with valid data – 1). All tests were performed with $\alpha = 0.05$.

The Kruskal-Wallis test rejects the null hypothesis of equality of distributions between days for all the variables analyzed ($p < 0.001$ in all cases). Relative humidity has the highest H statistic ($H = 2890.69$), followed by temperature and combustible gas, while dust and CO₂ have the lowest H values. The results confirm that genuinely distinct environmental conditions were captured, which validates the representativeness of the dataset for the analysis of the spatiotemporal variability of air quality.

4.3 Quantitative Results of the Flight Tests

To characterize the temporal behavior of the monitored variables, two daily flights of approximately 15 minutes each were performed during November and December 2025. The recorded data (temperature, pressure, dust, humidity, gas, and CO₂) were stored in a structured database and processed to generate the plots in Figure 7.

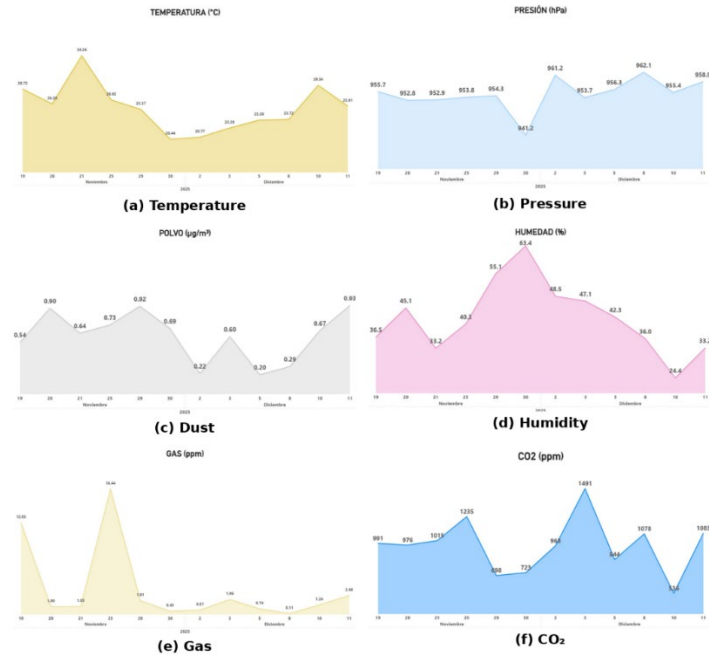


Figure 7. Plots of collected data: (a) temperature, (b) pressure, (c) dust, (d) humidity, (e) gas, and (f) CO₂.

The meteorological variables show a dynamic consistent with seasonal changes and local atmospheric conditions. Temperature presents moderate fluctuations, declining toward the end of November and recovering progressively in December; these thermal variations can directly influence atmospheric dispersion and stratification. Atmospheric pressure remains relatively stable, with a significant drop toward the end of November followed by an increase in early December (Figure 7b), suggesting changes in meteorological systems that could have modified air-stability conditions on certain days. Relative humidity shows marked oscillations throughout the period (Figure 7d), which can affect pollutant dynamics, particularly the formation, hygroscopic growth, and persistence of suspended particulate matter. Dust concentration (PM) presents notable variations, with well-defined peaks and drops between November and December, which could be associated with changes in industrial activity and with atmospheric conditions that favor or limit dispersion. The gas variable (ppm) shows high variability, suggesting intermittent emission episodes or changes in the intensity of specific processes within the monitored area (Figure 7e)—isolated variations that static systems might not detect. In contrast, CO₂ presents more stable behavior, with less pronounced variations than gas and dust (Figure 7f). This stability can be interpreted as a more constant emission associated with continuous combustion, making it a useful background indicator for contextualizing the other pollutants.

Overall, the temporal analysis confirms that the meteorological variables influence the variability of the recorded pollutants, and the drone's periodic, spatially distributed measurements made it possible to identify daily patterns and episodes of higher concentration. These visual patterns are consistent with the quantitative results: the inverse relationship between temperature and dust ($r = -0.401$) is reflected in the opposite trends of Figures 7a and 7c, while the marked variability of CO₂—which in Table 2 shows the highest standard deviation in absolute terms (SD = 499.86 ppm)—explains its more pronounced oscillations. These differences between days are statistically significant according to the Kruskal-Wallis test ($p < 0.001$), so the reading of the figures is supported by the statistical associations and the significant differences reported in Tables 3 and 4.

It is worth clarifying the relationship between the reported figures: the 3,610 records correspond to the total continuous raw readings acquired throughout all flight days, including the displacements between points. After cleaning and retaining the readings associated with valid coordinates at the five sampling points, the final dataset of 832 geo-referenced samples was obtained. The descriptive statistics (Table 2) and the training of the classification models were performed on this final set, whereas the Pearson (Table 3) and Kruskal-Wallis between-days (Table 4) analyses were computed on the continuous record of valid readings for each variable, which explains the different sample sizes and degrees of freedom. This controlled-collection strategy—fixed locations, defined time intervals, and a reduced number

of classes—gives the dataset a structure suitable for spatial-classification tasks. The relative simplicity of the models also favors a stable training process under these data conditions, maintaining consistent performance across the analyzed scenarios.

4.4 Critical Discussion

The results reflect the relevance of UAV-based environmental monitoring for assessing air quality in industrial environments, within the framework of the maximum permissible limits established by Mexican regulations and the WHO guidelines. Integrating meteorological variables with pollutant concentrations allowed a more precise interpretation of emission behavior and dispersion, revealing the complex interaction between pollutant sources and local atmospheric conditions. The variability observed in dust and gas levels highlights the temporal dynamics of industrial activities and their sensitivity to climatic factors, while the relative stability of CO₂ provides a constant reference for contextualizing the fluctuations of other pollutants. The system's ability to identify daily patterns and possible episodes of elevated concentration provides valuable information for environmental decision-making and preventive measures. In this sense, aerial monitoring represents a strategic complement to traditional monitoring, especially in areas that are difficult to access or where spatial coverage is limited. Taken together, these findings underscore the potential of UAV monitoring to support compliance with current regulations and a more efficient and responsible management of atmospheric emissions.

5. Conclusions

The use of drones for atmospheric pollution monitoring proves to be more efficient and accessible than traditional static stations. Their mobility makes it possible to evaluate multiple points, including those that are difficult to access, generating a more representative and accurate mapping of emissions. Unlike fixed stations, which limit measurement to a single point and require considerable investment in acquisition, installation, and maintenance, the drone offers a low-cost solution with less infrastructure without sacrificing accuracy. This makes it easier for small and medium-sized enterprises to incorporate advanced environmental-monitoring technologies, optimize resources, and strengthen their commitment to sustainability and regulatory compliance.

The developed system incorporates a functional IoT architecture based on a Raspberry Pi 5, which manages data acquisition, storage in an SQL database, and real-time visualization through a dashboard accessible within the same network. This client-server structure provides a solid basis for the expansion of the system, allowing local remote access, structured organization of the information, and continuous monitoring without depending exclusively on on-board processing. In its current configuration, the system operates with a single aerial platform; however, the implemented architecture would allow enhancements for the integration of multiple drones as additional acquisition nodes. The incorporation of more platforms would make it possible to increase the spatial density of sampling, improve the temporal frequency of data collection, and generate more dynamic and representative environmental maps. With adjustments in flight synchronization, concurrent data management, and communication coordination, the system can evolve toward a distributed network of mobile environmental monitoring, maintaining its modular and low-cost approach.

Other studies have also demonstrated the effectiveness of drones for atmospheric pollution mapping, such as Cozma et al. (2022), a study that developed a multipurpose autonomous aerial platform that made it possible to perform real-time measurements of atmospheric pollutants in urban areas, generating high-resolution maps that reflect the spatial distribution of pollution. As with our system, this approach confirms that the mobility and flexibility of drones represent a substantial advantage over static stations, since they enable more representative and dynamic sampling. The agreement in the results obtained reinforces the idea that sensor-equipped drones constitute a strategic tool for regulatory compliance and the sustainable management of air quality.

6. Study Limitations

- **Simulated validation environment:** Although the system was successfully tested and validated, the experimental tests were carried out in a semi-controlled environment (FIME–UANL soccer fields) and not in complex urban or high-density industrial scenarios. This means that variables such as intensive vehicular emissions, direct industrial sources, structural interference from tall buildings, and the dynamic conditions typical of metropolitan areas were not fully represented. Therefore, the system's behavior could vary when implemented in highly congested urban environments.

- **Sensor quality:** The system uses low-cost commercial sensors (MH-Z19B, GP2Y1010AU0F, DHT22, and BME280) which, although suitable for prototypes and academic applications, present inherent limitations in terms of accuracy, long-term stability, and possible deviations due to decalibration. Compared with certified environmental-monitoring stations, these sensors may present larger error margins, especially under variable environmental conditions. Specifically, this study did not perform a cross-validation of the measurements against certified reference stations operating simultaneously and co-located (co-location); for this reason, the values obtained must be interpreted as relative, exploratory estimates and not as absolute measurements with metrological validity. Such a validation constitutes a necessary line of work for future measurement campaigns.
- **Adverse weather for sampling:** Environmental factors such as strong wind, rain, extreme temperatures, and high humidity can affect both the stability of the drone and the quality of the measurements obtained. These conditions can introduce variability in the data and affect the consistency of the measurements.
- **Limited sensor diversity:** An important limitation was the difficulty in finding sensors suitable for measuring certain types of atmospheric pollutants, which restricted the diversity of variables evaluated in the study. In several cases, the commercial availability of sensors was limited or their cost was too high for drone applications. Among them, we can mention ultrafine particulate matter (PM₁), among others.

7. Study Contributions

7.1 Technical Contributions

From a technical standpoint, the combination of heterogeneous low-cost sensors mounted on a drone, integrated into an IoT architecture for real-time acquisition and management, demonstrates that it is possible to obtain multivariable atmospheric measurements without resorting to expensive specialized monitoring equipment. This contribution solves a real instrumentation problem: simultaneously bringing into the air different types of sensors with different communication protocols, operating ranges, and power requirements, keeping them functional under the vibrations and conditions inherent to flight. Unlike fixed stations that capture data at a single geographic point, the system makes it possible to generate pollutant-distribution maps over areas of variable extent, adapting the flight trajectory according to the measurement objectives. This dynamic-mapping capability represents a technical advance in the spatial characterization of air quality, making it possible to identify concentration gradients, locate emission sources, and assess pollutant dispersion with a spatial resolution that static stations cannot achieve.

7.2 Academic Contributions

The study establishes a documented and replicable methodology for the design, construction, and validation of atmospheric-monitoring systems based on drones equipped with commercial sensors. This constitutes an academic reference for future research in air quality, remote sensing, and embedded systems, providing a technical roadmap that other research groups can adapt to different geographic contexts, target pollutants, or aerial platforms. The development of the system places the research at the frontier between multiple disciplines, such as the design and operation of aerial platforms, the integration of embedded systems, and the measurement of environmental variables. This multidisciplinary convergence enriches the academic field by demonstrating that complex environmental-monitoring problems can be addressed from applied engineering, opening spaces for collaboration between areas that traditionally operate independently.

7.3 Industrial Contributions

For industrial companies, especially small and medium-sized ones, the system provides an emission-monitoring tool that meets the basic requirements of environmental tracking at a fraction of the cost of a certified station. For example, Horiba's AQMS costs about USD 150,000–200,000, whereas the developed drone costs approximately USD 3,000—a difference of more than 95% in initial investment. Where compliance with maximum permissible limits is a regulatory obligation, this in-house, low-maintenance solution reduces dependence on external measurement services and enables more frequent and flexible monitoring campaigns, helping small and medium-sized industries meet emission regulations autonomously.

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