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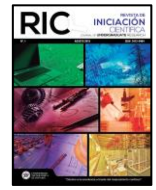

Lessons from a Low-Cost Sensors Campaign and CFD simulation when assessing urban air pollution

Lecciones del uso de sensores de bajo costo y CFD para evaluar la contaminación atmosférica urbana

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Abstract. Air pollution is a common secondary consequence of urban growth; however, in developing countries, where air quality management is often inadequate, strategies and methodologies to estimate atmospheric pollutants are necessary. This article summarizes a Low-Cost Sensors campaign and Computational Fluid Dynamics (CFD) simulation efforts to assess urban air pollution, considering requirements, methodology, and analysis of the results. Four prototypes were assembled to monitor air pollutants in Panama City, and a statistical analysis was conducted. A three-dimensional computational domain was simulated, featuring a busy road with two footbridges and four bus stops. The results indicated a significant limitation of Low-Cost Sensors due to accuracy, but they offer an affordable option for community engagement. The CFD simulation reflected wind distribution, but it did not account for scalar transport. Moreover, lessons were drawn regarding prices, expertise, time, and purposes for both methodologies.

Keywords. Air pollution, carbon monoxide, CFD, community science, low-cost sensor.

Resumen. La contaminación atmosférica es una consecuencia secundaria del crecimiento urbano. Sin embargo, en países en vías de desarrollo carecen de estrategias y metodologías para evaluar contaminantes atmosféricos en áreas urbanas. Este artículo resume una campaña con sensores de bajo costo y una simulación usando dinámica de fluidos computacional (CFD) para evaluar la contaminación atmosférica urbana, considerando requisitos, metodología y análisis de los resultados. Para la campaña de monitoreo se ensamblaron cuatro prototipos para monitorear contaminantes atmosféricos en la Ciudad de Panamá y se realizó un análisis estadístico. Además, se simuló un dominio computacional tridimensional de una carretera con dos puentes peatonales y cuatro paradas de autobuses. Los resultados indicaron una limitación en la precisión de los sensores de bajo costo, pero ofrecen una opción asequible para hacer ciencia comunitaria. La simulación de CFD reflejó la distribución del viento, pero no el transporte de contaminantes. Como resultado, se presentan las lecciones aprendidas relacionadas al costo, experiencia requerida, tiempo empleado y si cumplen el propósito de la contaminación atmosférica urbana.

Palabras clave. Contaminación del aire, monóxido de carbono, CFD, ciencia comunitaria; sensor de bajo costo.

1. Introduction

Air pollution, as defined by the World Health Organization [1], is the contamination of the indoor or outdoor environment by any chemical, physical, or biological agent that modifies the natural characteristics of the atmosphere compared to a reference baseline. It is a typical secondary result of city growth, as we produce, transport, and consume food and goods, and due to the demand for energy for cooling or heating and lighting in places where we live and work [2].

According to the United Nations Economic Commission for Latin America and the Caribbean (LAC) [3], 8.2% of the world's population resides in this region, with a staggering 79% living in urban areas. However, this reality is marred by socioeconomic inequality, air pollution, poor waste management systems, and a lack of health and urban infrastructure access. As [4] pointed out that most countries in the LAC region lack environmental policies or do not enforce them, particularly those related to air pollution. [5] highlighted that air quality monitoring sites are scarce, and the annual mean of inhalable particle concentration in most cities exceeds the World Health Organization Air Quality Guidelines.

In developing countries, air quality management is often deficient, and as the public socio-environmental awareness growth, there is an urgent need for methodologies to accurately estimate the concentration of atmospheric pollutants, particularly near hotspots.

1.1 Use of Low-Cost Sensors (LCS) for the Study of Air Quality

Monitoring air pollution is crucial in air quality management; however, not all countries can afford to establish monitoring networks due to the high costs and logistical challenges involved. In many developing countries, such as Panama, air quality management has not been established, and likewise, there are no assurance standards for instrument calibration, data collection, and post-processing.

The use of LCS in air quality monitoring has gained popularity due to relatively low prices, access to electronics platforms such as Arduino and Raspberry Pi, easy purchase through local electronics stores or e-commerce, and public awareness of environmental issues. In recent years, more accessible monitoring technologies have influenced environmental policymaking, as air quality data has become more readily available, enabling policymakers to make more informed decisions regarding air quality regulation and management. LCS can be used to locate pollution hotspots, identify sources of pollution, supplement fixed-site monitoring data, measure personal exposure to pollutants, educate the public, and enhance air quality awareness. For example, more monitoring information has increased the volume of data available and allowed community engagement, one of the cases is the initiative “Aire Ciudadano” in Bogotá Colombia [6]. Aire Ciudadano has been operating since 2017 in various locations within Bogotá, primarily utilizing public transportation TransMilenio. In Brazil, the campaign “Clean air for a good start” has highlighted the im-portance to reduce children exposition to air pollution, especially of $PM_{2.5}$ [7]. Also, in Methow Valley in the State of Washington in the United States of America the citizen science program selected “Clean Air Ambassadors (CAAs)” to host low-cost air sensors based on their geographic location and interest in air quality to monitor air pollution levels related to wildfires, winter wood stove use and prescribed and agricultural burning [8].

In Panama, some authors have ventured into the use of sensors for air pollution monitoring; some isolated air pollution monitoring campaigns, like the study conducted by [9] in David City, Chiriquí Province, where carbon monoxide (CO), carbon dioxide (CO_2), humidity, and temperature were monitored. Another project by [10] proposed an air monitoring station network across the Universidad Tecnológica de Panama campuses, measuring ozone (O_3), CO, and sulfur dioxide (SO_2).

Despite the rise in popularity, most authors are conscious of the performance of air quality monitors in comparison with reference methods [11, 12] , and the issues that need to be addressed, such as purposes, a lack of quantitative specifications from manufacturers, and a consensus on minimum performance goals. In countries with established monitoring networks, there has been a shift in air quality monitoring, where networks have transitioned from being government-operated to incorporating LCS technologies, accompanied by a growing interest in machine learning and advanced data processing to enhance monitoring accuracy [13].

Moreover, the review of the literature shows that the words sensor and low-cost sensors (LCS), are used interchangeably, and quoted in many documents as the equipment in charge of air quality monitoring, instead of being mentioned as part of the monitoring system [14-16]. However, an air quality monitoring system, also called sensor platforms, sensor systems, low-cost sensing, or Low-Cost Monitors (LCM) comprises the measuring component (the sensor), the enclosure or protective box, the data display (optional), power system (a battery or other power source connection), electronic hardware, and software for data acquisition, analogue to digital conversion, data treatment, and data transfer and varying components for data storage, transmission, and retrieval, represent the complete description. For this article, after explaining the difference, we will lean towards the phrase Low-Cost Sensor due to public familiarization.

1.2 Use of Computational Fluids Dynamics (CFD) for the Study of Air Quality

Since decades ago, for the study of air pollution, mathematical models supported by computational capabilities have been employed, such as Gaussian plume dispersion models, Lagrangian models, Eulerian models, remote sensing and satellites, and Computational Fluid Dynamics (CFD) [17].

Mathematical models are used to simulate and predict air pollution levels by incorporating factors like emissions, meteorology, and chemistry. Advances in computational tools have helped fill gaps in areas with scarce monitoring stations and recreate past situations or assess future scenarios. At the local stage, the Gaussian dispersion models have been employed by [18] to describe the environmental impact of the biggest landfill in Panama City using AERMOD. Also, the study by [19] employed CALPUFF-WRF to analyze the PMx, NOx, and SO_2 dispersion by the Thermoelectric of Miraflores in the Panama Canal.

Other studies have used remote sensing and satellites [20] due to the increasing popularity of initiatives such as the AURA from NASA [21] and SENTINEL-5 from ESA [22], they provide relevant information about air quality on a regional scale. However, these tools have not been fully exploited in the Panamanian isthmus because the satellite information has low resolution and is sometimes blocked by clouds.

A tool focused on studying fluids through pipes and machinery, later employed to study air pollution, is CFD. CFD is used to study air pollution because pollutants move through fluids, primarily air. CFD has been used to understand how particles or gases disperse in an environment, which is helpful for air quality studies, allowing for the representation of local phenomena and addressing air pollution near hotspots. Air pollution varies over different scales, representing the pedestrian level of utmost importance because it is usually located near the emission source and with atmospheric conditions that require considerations such as turbulence.

CFD has been shown to capture the characteristics in the microscale of a target area, considering meteorology, geography, and pollutant emission and dispersion [23-25] by solving the Navier-Stokes equations for fluid flow, CFD allows for repeating scenarios or parametric evaluation and provides more detailed information about the domain under study. While describing air pollution, CFD analysis combines fluid mechanics, numerical analysis, and data processing to study fluid flows [26-29]. Advances in computer power have allowed the extension of the versatility of its use in urban environments, including solar radiation [30], chemical models [24] [31], urban ventilation [32-34], etc. Despite the advances in CFD, validation is still required, and sometimes the software must be purchased, making it difficult to acquire.

Even though this tool has been employed in many latitudes, in Panama, not so many have addressed air pollution with this methodology [35, 36].

The objective of this article is to provide guidance to the assessment of urban air pollution when employing Low-Cost Sensors (LCS) or Computational Fluid Dynamics (CFD) simulations. Despite the rise in the use of LCS and the application of CFD to evaluate microscale environments, these two methodologies have not been outlined to understand their advantages and disadvantages in regions with weak air quality management systems.

2. Methodology

2.1 Comparison of Low-Cost Sensors and CFD to study air pollution

LCS and CFD have been employed in the study of air pollution in urban areas, but they imply different steps to accomplish that purpose. Figure 1 shows the considerations to achieve results with both methodologies, providing a reference for selecting one of them to study urban air pollution.

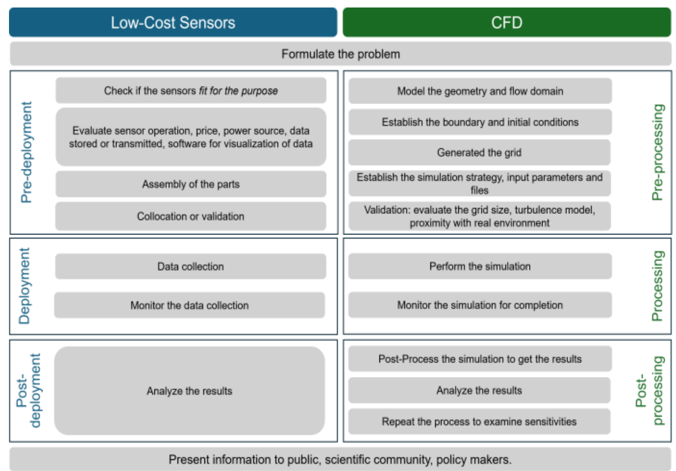

Figure 1. Considerations when using LCS or performing CFD simulations.

Initially, when using LCS or CFD, the problem must be formulated to determine whether air pollution is related to a point source, mobile source, personal exposure, or hotspots. In the case of LCS, the actions could be divided into three main categories: pre-deployment, deployment, and post-deployment. The deployment consists of identifying the objective of the monitoring to understand if the sensor will be able to sense the information required [13]. Then, to make decisions related to sensor operation, price, power source, whether the data will be stored or transmitted, and how the data will be displayed later. Next, it is the ability to assemble the component for the breadboard, preboard, or stripboard. Once the monitor is assembled, the next step will be to evaluate its performance alongside a certified monitoring station to verify the validity, accuracy, and precision of the measurements. This step is referred to as collocation or validation, and it is the most important.

Once the monitors' performance is known, it is time to collect data at the location where the pollutant concentrations are to be determined. The data can be monitored in real-time or stored and later analyzed. After post-deployment, the results are analyzed and presented to the public, scientific community, and policymakers.

On the other hand, CFD will also require defining the problem to be described, which could be a past event or a future scenario. The preprocessing part will require drawing the geometry (domain) and establishing boundary and initial conditions (the second in the case of a transient simulation); the grid will allow solving the Navier-Stokes equation, the Scalar transport equation, or the Chemical reaction equation. The simulations will recreate a laminar or turbulent flow depending on the phenomenon. In the case of turbulent flow, the best turbulence model should be decided (k-ε, RNG, Realizable, k-ω, LES, among others). The numerical method to solve the discretized equations must also be established. Despite some studies not conducting validation of the grid, turbulence model, or similarity with real conditions, this step is recommended. Then, the subsequent part will involve running the simulations, and the time required will depend on the settings and computer capabilities. Some software allows for the monitoring of real-time residuals to determine the convergence of the simulation. The postprocessing part will show the results and, depending on the study, make a comparison with wind tunnel experiments or other benchmark simulations. If required, the procedure would be repeated to examine sensitivity. Colors are used to represent wind speed, vector, or pollutant concentrations. However, the results must be adequately presented to the public due to the high requirement for logical and mathematical interpretation.

2.2 Description of the area of analysis and local weather conditions

In 2023, the demographic census indicated that more than 50 % of the Panama Republic's population lives in the Provinces of Panama and West Panama [37]. Moreover, 70% of the vehicular fleet is registered in Panama Province [38]. Traffic is conditioned by people moving from the west side of the Panama Canal, from the so-called “dormitory cities” to Panama City. Two bridges, the Centennial Bridge (in Spanish: Puente Centenario; 9° 1' 54.13‘' N 79° 38' 2.71" W), and the Bridge of the Americas (in Spanish: Puente de las Americas; 8° 56' 34.40‘' N 79° 33' 58.43" W) connect the west side with the center, prompting a funnel effect (figure 2).

The Universidad Tecnologica de Panama is a public institution dedicated to higher education. Its main campus is Victor Levi Sasso (9° 1' 33.27" N 79° 31' 46.48" W), located next to Avenida Centenario, one of the roads connecting the west with the east through the Centennial Bridge.

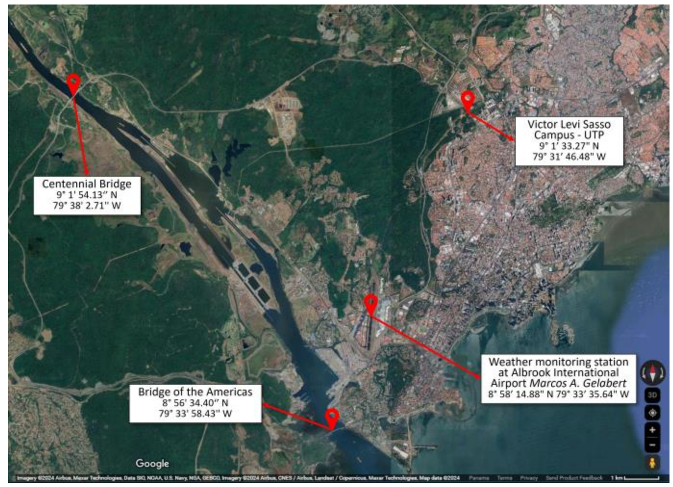

Figure 2. Victor Levi Sasso Campus (9° 1’ 33.27" N 79° 31’ 46.48" W) of the Universidad Tecnológica de Panamá is located near a busy road, Avenida Centenario. The nearest weather monitoring station is in the Albrook International Airport “Marcos A. Gelabert” (8° 58’ 14.88" N 79° 33’ 35.64" W). Google Maps 2024.

The nearest weather monitoring station to the Victor Levi Sasso Campus is located at the Albrook International Airport “Marcos A. Gelabert” (8° 58’ 14.88" N 79° 33’ 35.64" W) at approximately 6 km radius at 10 meters from the ground (Figure). A monitoring campaign was conducted at the Victor Levi Sasso Campus entrance on December 13, 14, and 15, 2023, using a portable weather monitoring station, the Davis Vantage Pro2 TM, to determine the local weather conditions. The portal weather monitoring station was set 1.2 m above the ground. The monitoring continuity using the portal weather monitoring station was contingent upon the rain and the team's safety. The data collected was compared to the weather monitoring station at the Albrook International Airport “Marcos A. Gelabert (Figure).

The weather station information for Albrook International Airport “Marcos A. Gelabert” was downloaded from the R package. The gray area in Figure shows consistently recorded days for the three days. Moreover, we can observe that wind speed and temperature exhibit similar behavior. Still, the wind speed is significantly lower than the record at Albrook International Airport due to surface roughness, and the temperature is slightly higher due to the built-up environment. The wind direction for those days, 13, 14, and 15, was west east, respectively.

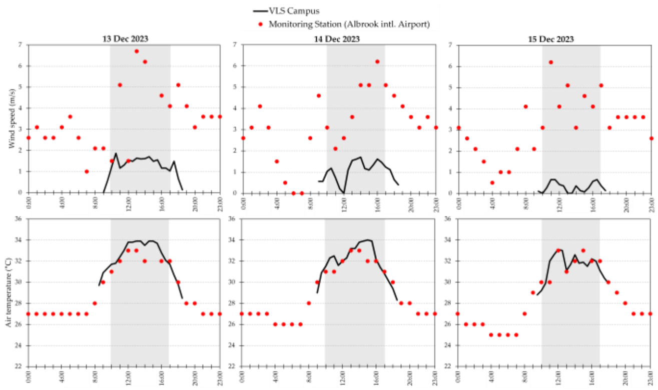

Figure 3. Comparison of wind speed (m/s) and air temperature (°C) for 13, 14, and 15 December 2023 from the portable monitoring station located at the entrance of the Victor Levi Sasso Campus of the Universidad Tecnológica de Panamá and the nearest monitoring station in the Albrook International Airport "Marcos A. Gelabert".

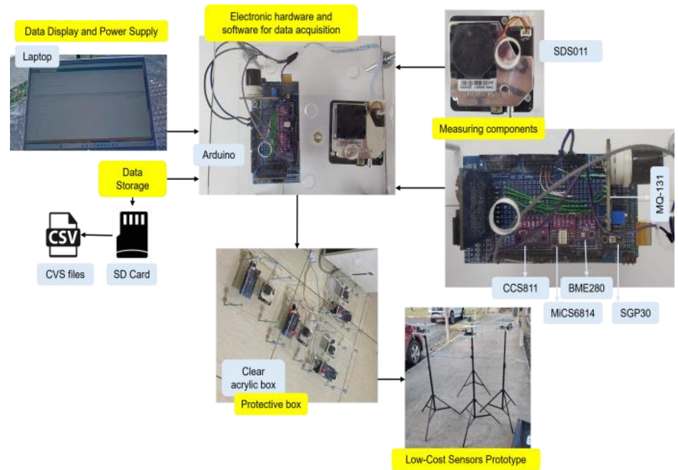

Figure 4. Assembly of the LCS Prototype.

2.3 Low-Cost Sensors Prototype Assembly

In general terms, the measuring component (the sensors) can be classified into two groups: those that measure gas-phase species and those that measure particulate matter. For this study, four blocks of LCS were assembled and labeled LCS-A, LCS-B, LCS-C, and LCS-D. The pollutants considered were Total Volatile Organic Compounds (TVOC), Carbon Dioxide (CO_2), Carbon Monoxide (CO), Tropospheric Ozone (O_3), and Particulate Matter 2.5 and 10 ($PM_{2.5}$ and PM_{10}). Moreover, temperature, humidity, and atmospheric pressure were monitored.

The gas sensors used in this project operate based on the metal oxide sensing principle. This detection mechanism relies on changes in the concentration of oxygen adsorbed on the surface of the metal oxide semiconductor. When trace amounts oxidizing or reducing gases meet the sensor surface, catalytic reactions occur with the adsorbed oxygen, which alters the material's electrical resistance. This change in resistance allows the system to detect both the type and concentration of the target gas. Sensors that operate under this principle include the CCS811, MiCS6814, SGP30, and MQ-131 (figure 4).

For particulate matter (PM) measurement, we used the SDS011 sensor, which works based on laser scattering. Laser light scattering is induced when airborne particles pass through the detection chamber. The scattered light is converted into electrical signals, which are then amplified and processed to determine the concentration of particles in the range of 0.3 to 10 µm. This sensor provides digital output and includes a built-in fan to ensure a constant airflow through the detection zone.

BME280 was employed to monitor relative humidity, barometric pressure, and ambient temperature. The BME280 is a small sensor with low power consumption.

The software for data acquisition was programmed using the Arduino platform. This project uses several libraries to read environmental sensors: Adafruit_BME280 to measure temperature, humidity, pressure, and altitude with the BME280 sensor; Adafruit_CCS811 to obtain CO_2 and TVOC levels; MQ131 to detect O_3; MiCS6814-I2C with analog pins to measure gases such as CO, NO_2, and NH_3 using the MiCS6814 sensor; Adafruit_SGP30 (although not actively used in the code) is also used to measure TVOC and CO_2; SdsDustSensor allow to obtain fine particle concentrations ($PM_{2.5}$ and PM_{10}) using the SDS011 sensor; RTClib provides the current time and date from a DS3231 RTC module; and finally, SD and SPI allow you to save the collected data to an SD card.8N3GROn. The code included specific functions to initialize sensors, acquire readings, format the data into CSV files, generate ISO-format timestamps, create uniquely named files, and store the data on an SD card. During the programming, the structure was divided into two main blocks: setup(), where all components are initialized, and loop(), which continuously performs data acquisition, visualization, and storage every two seconds.

The sensors were soldered onto a shield board and connected to an Arduino mounted on an acrylic frame attached to a 1.5 m tripod. The system was powered through the Arduino COM port, using a laptop battery during data collection.

2.4 CFD Settings

A three-dimensional domain was simulated using COMSOL Multiphysics 6.2. The computational domain includes a busy road with two footbridges and four bus stops. The bus stops in front of the National Rehabilitation and Physical Medicine Institute (9° 1' 42.21" N 79° 31' 46.86" W) are built with elevators and handicap-accessible ramps. The footbridge's height is H: 6.15 m, and the rest of the dimensions were obtained following [39] recommendation; inlet, lateral, and top boundaries 5H max, the outflow boundary was at least 15H max away from the group of buildings to allow for full wake flow development. The size of the calculation domain was in stream-wise (x), span-wise (y), and vertical (z) directions were 550 m × 450 m × 50 m, respectively. Three unstructured tetrahedral meshes were evaluated: mesh A (296 045 elements), mesh B (607 194 elements), and mesh C (2 383 621 elements). The simulations were conducted using Mesh B due to the analysis of the results versus computational cost.

As indicated in section 2.2, the boundary conditions of the CFD domain for wind speed and wind direction were obtained from the portable weather monitoring station. The wind direction was set from the west. 14 December 2023 was chosen as the calculation date for the stationary CFD analysis, and a velocity inlet of 1.55 m/s was specified. Symmetry boundary conditions were applied at the top and sides, a pressure outlet at the outlet, and no-slip conditions on the ground and building blocks.

In the CFD Module of COMSOL Multiphysics 6.2, the standard k-epsilon (k-ε) turbulence model was set. The inlet boundary condition for the turbulence intensity was defined as 0.05, and the turbulence length scale was 0.01. Air was modeled as incompressible, isothermal, and steady-state, without external forces. Mass and momentum conservation equations were discretized using the finite element method.

3. Results

3.1 Comparison of LCS and CFD to study air pollution

The monitoring campaign was conducted at the Victor Levi Sasso Campus entrance on December 13, 14, and 15, 2023, on Avenida Centenario. After the data was collected, it was processed and organized for each LCS, specifically for carbon monoxide (CO). The other pollutants were discarded due to inconsistencies in the reading and a lack of validation with the reference monitoring station. Before the monitoring, a 30-minute calibration period was conducted. A basic statistical analysis was conducted to identify the patterns of the monitored CO, including the calculation of the average, median, mode, minimum, maximum, and standard deviation (table 1). Data cleaning involved reviewing the total data obtained for each day during the periods from 9:00 to 11:00 and from 15:00 to 18:00. The data obtained was averaged every 5 minutes within the chosen time range.

Table 1. Descriptive Statistics of the LCS and Correlation Analysis of the Low-Cost Sensors vs the Reference Air Monitoring Station

Descriptive Statistics of the LCSow-Cost Sensors				
	LCS - A	**LCS - B**	**LCS - C**	**LCS - D**
# of samples	150	88	121	58
Average	48.2	59.3	74.3	65.7
Median	61.5	114.0	123.0	117.3
Mode	73.3	10.5	59.0	106.0
Standard deviation σ	33.9	65.6	62.0	45.3
Minimum	11.3	8.0	11.7	7.5
Maximum	153.7	220.0	219.0	194.5
Correlation Analysis of the LCS vs the Reference Air Monitoring Station				
	LCS - A	**LCS - B**	**LCS - C**	**LCS - D**
Typical Error	30.2	47.9	37.5	29.7
Average humidity (%)	53.7	50.5	51.4	45.5
p-value	0.2588	3.46E-07	3.29E-06	3.68E-03
Correlation coefficient (R)	-0.0928	0.4989	0.4052	0.3669
Determination coefficient (R^2)	0.0086	0.2489	0.1642	0.1346
Comments	There is insufficient evidence of a linear relationship.	There is a statistically significant relationship of moderate strength.	Significant relationship, although somewhat weaker than in B.	Significant but weaker correlation.

As we mentioned, no public monitoring station exists in the Republic of Panama. However, the values were compared against those of a low-cost monitoring station branded AirSENCE used for research purposes, located at the Victor Levi Sasso Campus of the Universidad Tecnológica de Panamá. The reference monitoring station simultaneously measures CO, $PM_{1.0}$, $PM_{2.5}$, PM_{10}, O_3, NO, NO_2, SO_2, temperature, humidity, and atmospheric pressure. The recordings of the AirSENCE and the four LCSs were compared using a correlation analysis to determine the relationship between the variables. The correlation was chosen because, in case studies involving LCS, it can be a fundamental tool [40, 41] for better understanding of the data obtained, as well as for correcting any errors and adjusting them to strengthen the quality of the measurement. When analyzing LCS, the correlation helps identify errors, such as a fault in the sensor or its programming. Another point is crosscalibration, as this analysis can be used to estimate values in sensors that have identified errors [42-45].

The correlation helped to evaluate the covariance relationship, that is, whether two variables change together. The results do not necessarily imply a cause-and-effect relationship but instead describe trends in the data. The results of the evaluation analysis comparing the LCS with the reference monitoring station reveal significant variability in the degree of linear association, which may be attributed to substantial differences in the performance or operating conditions of each device (table 1).

As can be seen in Table 1, for LCS-A, a very low negative score is observed ($R = -0.0928$; $R^2 = 0.0086$) and a p-value = 0.2588, indicating that there is no statistically significant linear association between its measurements and those of the reference monitoring station. This behavior contrasts with that of LCS-B, LCS-C, and LCS-D, which show moderate positive correlations with values ranging from ($R = 0.37–0.50$). These correlations are statistically significant, as indicated by the p-value.

It is essential to note that although both devices (LCS and the reference air monitoring station) exhibit similar trends in certain sections, for LCS-B, LCS-C, and LCS-D, the relationship between them is not strong enough to be considered reliable without prior calibration.

Moreover, an analysis of the RMSE of carbon monoxide (CO) in the morning and afternoon on December 14, 2023, for the LCS-A was evaluated to compensate for the variables. The RMSE in the morning was 192 ppm, and in the afternoon, it was 238.80 ppm. For the period evaluated, an underestimation was observed.

All the statistical analysis differences could be due to calibration problems or deterioration, poor condition or quality of the sensor at the LCS, different local conditions, such as inappropriate location, environmental interference, or microclimatic differences, and structural and technical problems with the sensors, such as reduced sensitivity to humidity or electronic instability.

3.2 CFD results

Due to computational cost, the simulation was only run for an hour in steady state on Thursday, 14th December 2023, at 13:00. The wind was input coming from the west to east (positive x-direction). Figure 5a shows an isometric view of the simplified microenvironment in the surroundings of the Campus Victor Levi Sasso, Centenario Avenue. The velocity field indicates that the wind is predominantly coming from the west, reaching values of 2.5 m/s throughout the domain (red color). Consequently, the regions with lower wind speeds are those leeward of the footbridges (blue color).

The region with lower wind speed is indicated in the blue area, which suggests where the highest concentration of pollutants will be, and it coincides with locations where pedestrians will be most exposed while walking, sheltering from sunlight, and waiting for transportation.

Figure 5b and figure 5c show that the influence of the wind flow in the roadway can be weakened, but since the turbulence due to traffic was not modeled, further analysis will be required. While the primary focus of this study was to analyze the transport of multiple pollutants due to traffic pollution, it was restricted to CFD module available; then, we will show the velocity field.

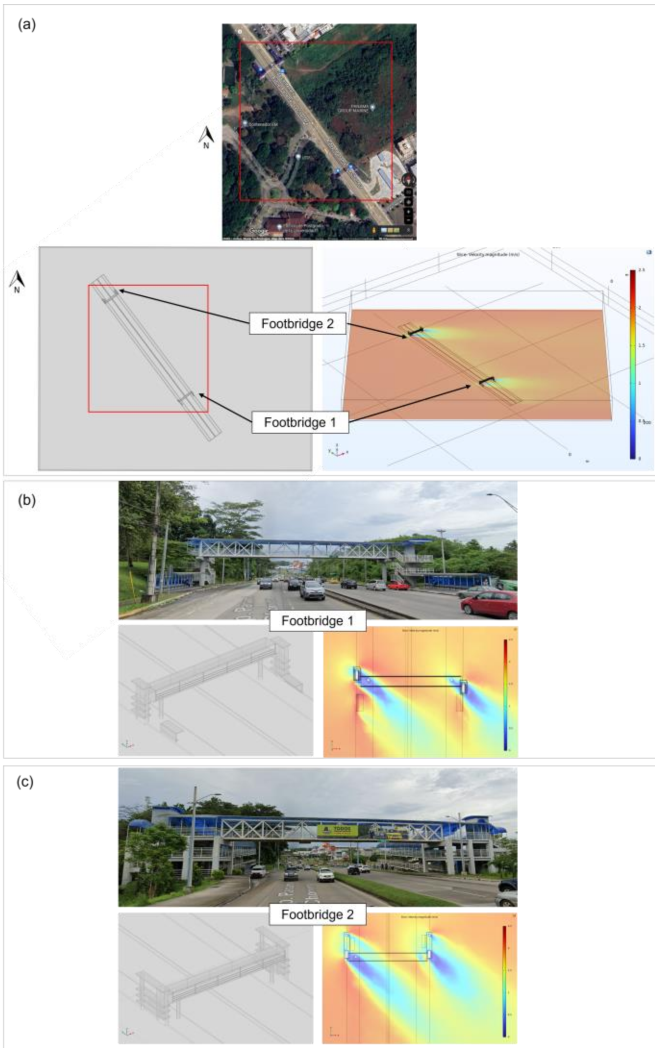

Figure 5. Isometric view and calculated domain and of (a) Avenida Centenario, Google Maps 2024 (b) View of the Footbridge 1, Google Maps 2024 View and the results of the simulation on Avenida Centenario (c) View of the Footbridge 2, Google Maps 2024 View and the results of the simulation on Avenida Centenario.

In figure 5, negative values in the average U-velocity fields behind the footbridges (on the east side) indicate wind flow recirculation in these areas. Recirculation zones are more pronounced behind structures aligned with the wind flow, as opposed to those at oblique angles to the wind direction. A closer examination of these recirculation zones is provided in Figure 3b and c. This phenomenon may be attributed to the abrupt change in terrain from an urban setting, caused by bluff body building.

4. Discussion

After using both methodologies to describe urban air pollution, the following lessons regarding price, maintenance, expertise, time, and purpose are discussed (figure 6):

- Price: even when LCS are named "low-cost", prices can start at $400 US Dollar per monitor when considering several sensors, communication, data components, and especially batteries or power supply (without considering the logistics involved in collocation or deployment). CFD simulations, for their part, will require the acquisition of software such as ANSYS Fluent, COMSOL, and Simflow, which entail annual license fees, placing a burden on government or academic institutions. Sometimes, the freely available option has mesh restrictions that imply constraints on the simulation's capabilities. On the other hand, in recent years, open-source CFD software is gaining popularity, such as [24, 46]. However, it will demand additional coding literacy from the users.
- Maintenance: LCS will require the replacement of components depending on their lifetime, some manufacturers indicate that the lifespan of sensors is up to two years. Also, the other components are very sensible to weather conditions. On the other hand, CFD requires a high computational resource that will need to be operative during the time of processing and post-processing.
- Expertise: both methodologies require a basic knowledge of air pollution from the users to analyze the data. LCS requires the proponent to have knowledge of computer science, electronics, and telecommunications. CFD simulation of mechanical fluids, differential equations, numerical methods, and CAD to draw the domain. However, using one of the other

	Low-Cost Sensors	CFD
Price	The sensor individually will lower 100 $, but the other components will sum up	Depend on the software to be used (Ansys Fluent, COMSOL, Simflow, OpenFOAM, Flowdesigner)
Maintenance	Replacement if often recommended after two years, depending on sensor. Considerations of location and weather must be evaluated.	Hardware functioning and capabilities could increase the operational cost (RAM, processors, GPUs)
Expertise	Knowledge in computer science, electronics, and telecommunications	Knowledge in differential equations, mechanical fluids, numerical methods, CAD
Time	At least 2 months even with experience	At least 2 months. Moreover, the simulations will depend on parameters
Purpose	Monitor real time concentration	Recreate past situations or predict future scenarios

Figure 6. Discussion about the use of LCS and CFD to study urban air pollution.

- Time: with complete dedication and prior knowledge, the assembly and execution of urban air pollution monitoring will require at least two months. However, in the case of LCS, the conditions need to be weather favorable and ensure the team's safety. The time will be spent on everything operating and functioning with minimum errors. The CFD simulation time will depend on the availability of input variables; if weather parameters are not available, they will need to be monitored to ensure a specific microenvironment condition is met. Moreover, if geography or urban geometry is not available, on-site measurements will be necessary. Also, emissions to specific locations will need to be collected.
- Purpose: the analysis from this article clearly defines that both methods obey different needs. LCS attempts to monitor real-time concentration, and the main advantage of CFD is to recreate past situations or predict future scenarios. Conversely, the use of CFD for modeling urban air pollution requires input variables such as weather conditions, urban geometry, and emission inputs. However, weak systems in developing countries often lack the necessary information or rely on information provided by other institutions, considering that they are responsible for collecting and recording this information. On the other hand, the real-time monitoring of LCS will be corroborated by comparison with reference monitoring stations; however, they cannot be used for regulatory purposes, and the recommendations suggest that validation or collocation should be conducted. Also, the duration and performance of the sensors throughout the time must be considered and evaluated every time.

5. Conclusions

This work highlights the steps involved when working with LCS and CFD. As mentioned by {Austin, 2015 #574}, the general recommendation for users of low-cost sensors or monitors is that they should be pre-tested or calibrated under the conditions under which they are intended to be used. However, we have identified that this is not easy in countries with poor air quality management. LCS offer an affordable solution; but their accuracy may not be sufficient to meet the air quality monitoring standards established by regulatory institutions and their performance depends on weather conditions.

Also, we found that academic institutions must diversify their curricula so students in environmental sciences, programming, chemistry or engineering have the skills to deal with sensors, coding, and electronics.

For the CFD simulation, the domain in our study was limited to terrain and buildings, without considering the impact of trees on wind flow and scalar distribution. While it is acknowledged that incorporating trees and additional objects in a CFD approach can present challenges and may be considered for future investigations to improve the simulations and help to account for these effects.

In conclusion, LCS and CFD are tools that will continue to be explored to study urban air pollution and by considering the lessons mentioned in this article the procedure will be better carried out, and maybe the resources could be better allocated.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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