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Monitoring air quality in residential areas with low-cost sensors: Santa Cecilia case

Monitoreo de la calidad del aire en zonas residenciales con sensores de bajo costo: Caso Santa Cecilia

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Low-cost monitoring; industrial emissions; fine particulate matter
Monitoreo de bajo costo, emisiones industriales, material particulado fino

ABSTRACT: The expansion of the industrial zone along the Medellín Highway on the northwestern outskirts of Bogotá has raised concerns among nearby residents regarding the potential health impacts of pollutant emissions. This study evaluates the behaviour of particulate matter with an aerodynamic diameter below 2.5 micrometres (PM2.5) in indoor environments of the Santa Cecilia neighbourhood, relative to outdoor atmospheric concentrations, using custom-designed low-cost sensors. In situ PM2.5 concentrations were compared with meteorological data and PM2.5 reports from the Bogotá Air Quality Monitoring Network (RMCAB). Data processing and wind analysis were conducted using Python and WRPLOT software. The results indicate that indoor PM2.5 concentrations are minimally influenced by outdoor pollutants (approximately 3%), with peaks of internal concentrations (up to 1661 µg/m³) attributed primarily to indoor activities and personal behaviours. Recommendations include the strategic use of natural ventilation to prevent excessive indoor PM2.5 accumulation during activities such as cooking and cleaning.

RESUMEN: La expansión de la zona industrial a lo largo de la Autopista Medellín, en las afueras noroccidentales de Bogotá, ha generado preocupación entre los residentes cercanos debido a los posibles impactos en la salud derivados de las emisiones contaminantes. Este estudio evalúa el comportamiento del material particulado con un diámetro aerodinámico inferior a 2.5 micrómetros (PM2.5) en ambientes interiores del barrio Santa Cecilia, en relación con las concentraciones atmosféricas exteriores, utilizando sensores de bajo costo con diseño personalizado. Las concentraciones in situ de PM2.5 se compararon con datos meteorológicos y reportes de PM2.5 de la Red de Monitoreo de Calidad del Aire de Bogotá (RMCAB). El procesamiento de datos y el análisis de vientos se realizaron mediante Python y el software WRPLOT. Los resultados indican que las concentraciones de PM2.5 en interiores están mínimamente influenciadas por contaminantes externos (aproximadamente un 3%), mientras que los picos de concentración interna (hasta 1661 $\mu g/m^3$) se atribuyen principalmente a actividades domésticas y comportamientos personales. Se recomienda el uso estratégico de ventilación natural para prevenir la acumulación excesiva de PM2.5 en interiores durante actividades como cocinar y limpiar.

1. Introduction

The current urban air pollution is the result of anthropogenic activities worldwide. These activities have led to a significant increase in atmospheric emissions and, consequently, higher concentrations of polluting gases and particles [1]. According to the World Health Organization (WHO) [2], more than half of the global population resides in cities that fail to meet the proposed safety levels for $PM_{2.5}$ (annual mean of 5 $\mu g/m^3$), with contamination rates often exceeding these limits by 2.5 times. The effects of particulate matter (PM) depend on its size; smaller particles are more likely to penetrate the human body, eventually depositing in the respiratory tract [3][4].

According to Piña [3], the human body has mechanisms to eliminate inhaled particles, but their effectiveness varies with particle size. For particles larger than 10 µm, removal efficiency is approximately 99%. Particles between 10 µm and 2.5 µm generally adhere to the mucous membrane and are eliminated from the lower respiratory tract. In contrast, fine particles smaller than 2.5 µm can easily penetrate the lungs, reaching the bronchioles and even entering the bloodstream. These fine particles, also known as breathable particles, pose a significant risk to human health.

In the Americas, 95% of the population is exposed to pollution levels exceeding WHO guidelines, with the majority of these individuals residing in developing countries [5]. In Colombia, air quality degradation has become an increasing problem, contributing to an estimated 15,684 annual deaths from respiratory, cardiovascular, and cerebrovascular diseases [6]. Studies in Latin America have identified Bogotá [7] and Lima [5] as cities with the highest concentrations of air pollutants and the most significant public health impacts related to respiratory diseases, including asthma, lung diseases, rhinitis [8], bronchitis, and persistent cough [9].

Significant knowledge gaps remain regarding population exposure to air pollution, particularly indoors. In many cases, the behaviour of micro-atmospheres inside buildings is not taken into account [10]. This leads to a lack of awareness among much of the population about the potential health effects of indoor air pollution, which may originate from outdoor airflow or activities performed within the property (e.g., cooking or cleaning). This is particularly relevant given that people currently spend 60% to 90% of their daily time indoors [11].

Air quality problems in closed environments may result from external pollutants, such as those from fixed sources (industries) or mobile sources (vehicles), as well as indoor activities, including combustion processes, smoking, and the use of cleaning products [12]. Inadequate ventilation further exacerbates these issues [13]. The kitchen, particularly due to the combustion of fossil fuels, is one of the most significant sources of indoor pollutants. PM concentrations vary depending on the kitchen's position, the type of fuel used, and the ventilation rates [14]. Additionally, residential characteristics—such as the number of windows, type of flooring, type of curtains, and air renewal rates—are crucial factors influencing pollutant concentrations due to their impact on air circulation from the outdoors [15].

Thus, the behaviour of PM inside homes depends on internal characteristics and emission rates, which are influenced by behavioural patterns and specific activities within the household. Understanding these dynamics is essential for assessing how pollutants affect the micro-atmosphere of a home.

It is also important to consider meteorological variables in the study area, as wind direction significantly impacts pollutant transport, dispersion, and penetration into buildings [15]. This is particularly relevant when residential areas are located near or within the vicinity of strong emission sources, such as industrial hubs or heavily trafficked highways.

In recent years, several companies and industrial hubs have relocated from Bogotá's urban core to nearby municipalities, often to larger facilities or areas with lower tax burdens. This shift has created new corridors for heavy vehicle fleets and industrial activity. One prominent example is the Medellín Highway on the outskirts of Bogotá, along Calle 80 (**Figure 1A**). This highway forms part of the western industrial corridor, which exemplifies the industrialization-urbanization-regionalization model [1]. Over the years, activity in this corridor has steadily increased. Business units in the area include cemetery parks, industrial parks, and manufacturing facilities.

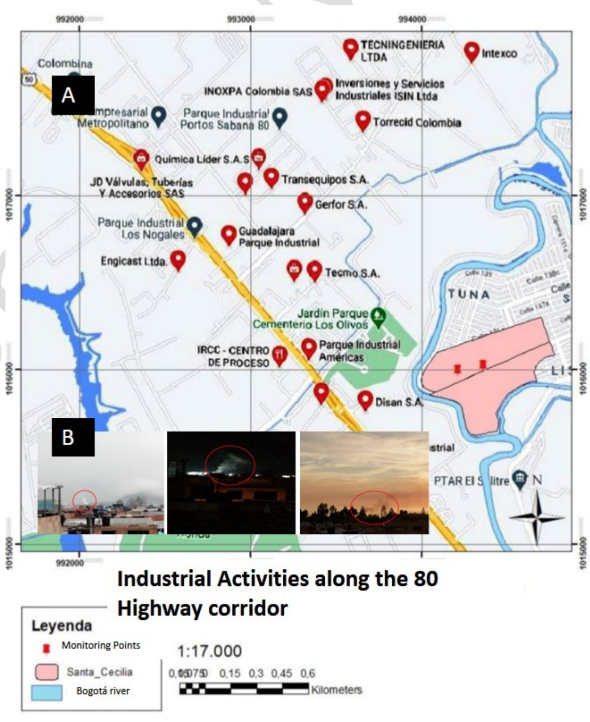

Figure 1 (A) Industrial activity of the western corridor on the Medellin Highway and (**B**) visible emissions from the neighbourhood.

There are approximately seven neighbourhoods in the town of Suba near the industrial zone, separated from it only by the Bogotá River. These include the Santa Cecilia neighbourhood (highlighted in pink in **Figure 1A**). This neighbourhood borders the municipality of Cota to the west, specifically the industrial zone of the western corridor within the municipality. From the study area, emissions from the industrial zone are clearly visible, creating a constant concern for residents about their potential health impacts.
In **Figure 1B**, emissions from the cemetery park and other industrial parks in the area can be observed. These neighbourhoods predominantly consist of residences classified as low or very low socioeconomic levels (strata 1 and 2). To date, no studies have evaluated the impacts of air pollution generated by this industrial zone on the residents of nearby residential areas. Conducting such studies is essential to understand the influence of these emissions on indoor air quality in surrounding homes and to guide residents in taking appropriate measures to mitigate exposure.
The determination of PM concentrations, both outdoors and indoors, often requires expensive equipment, making such studies financially inaccessible for communities with limited resources or for researchers working in low-income areas. However, recent advances in microelectronics and telecommunications are paving the way for low-cost instruments that can address these limitations. Low-cost sensors have emerged as valuable complements to existing air quality monitoring networks [17], aiding in the control and assessment of environmental pollutants.
According to Maldonado and Rojas [18], these systems typically operate in three stages. The first stage, known as Perception, includes the physical sensors used to capture data on the pollutant(s) under study. The second stage, called Network, serves as the connection point between the sensor data, and the third stage, transmitting information to storage servers. The final stage, Application, involves analysing the data, allowing real-time capture of pollution levels to generate diagnoses and forecasts of pollutant behaviour.
These technologies have the potential to significantly enhance the resolution of pollution analysis in both open environments and microenvironments, thereby enabling the assessment of exposure in all locations where the population resides or spends significant amounts of time.
This study seeks to evaluate the behaviour of particulate matter in both outdoor and indoor environments within the Santa Cecilia neighbourhood using low-cost monitors. Additionally, it aims to determine whether these PM concentrations are primarily influenced by the industrial zone along the 80th Highway corridor or by indoor activities. To achieve this, the study also examines prevailing meteorological conditions in the area to infer the transport trajectories of particulate matter.

2. Materials and methods.

This project is a descriptive study designed to determine the concentration of fine particulate matter (PM2.5) indoors in relation to outdoor concentrations at nearby residences and to assess their potential connection to the industrial zone located along the Medellín Highway. The study also considers the meteorological variables prevailing in the area.

The project was carried out in three distinct phases to achieve the proposed objectives, as described below.

2.2 Phase I: Meteorological Characterization of the Study Area

A meteorological analysis of the area was conducted to identify variables such as wind direction and speed, temperature, and relative humidity (RH) on an hourly basis. The data for this analysis were obtained from the Bogotá Air Quality Monitoring Network (RMCAB, by its Spanish name) stations located near the study area: Suba Station, Bolivia Station, and Las Ferias Station (**Figure 2**).

The meteorological data from RMCAB were processed using commercial spreadsheet software and WRPLOT (Wind Rose Plot Software) to construct wind roses. WRPLOT, developed by Lakes Environmental, generates wind roses using meteorological data, including wind speed, direction, and frequency. The software employs a polar coordinate system, where the radius of each sector represents the frequency of wind occurrence in a given direction. Wind speeds are categorized into intervals, which are illustrated with distinct colours or shading in the wind rose. These calculations are based on a statistical aggregation of hourly wind data, providing a clear visualization of prevailing wind patterns over a defined period.

Figure 1. Stations of the Bogotá Air Quality Monitoring Network (RMCAB) near the study area, Monitoring points in the Santa Cecilia neighbourhood.

2.2. Phase II: Determination of particulate matter concentrations in the study area (interior and exterior)

During a total period of 12 days between October 20 and October 31, 2020, the meteorological conditions and concentration of particulate matter in the Santa Cecilia neighbourhood were monitored. The concentrations of particulate matter were measured in situ using low-cost sensors, simultaneously with the concentrations reported by the RMCAB stations.

2.2.1. Sampling points in situ

The monitoring points located in the Santa Cecilia neighbourhood comprise two residential houses (Casa 1 and Casa 2, see **Figure 3**). Four monitors one pair for each residential house (2 internal and 2 external) were fitted, with particulate matter (PM2.5), temperature and relative humidity sensors. Monitoring was carried out 24 hours a day simultaneously at all four points.

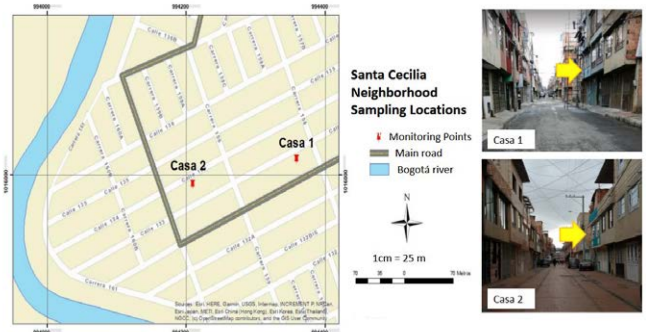

Figure 2 Location of sampling points at Barrio Santa Cecilia

The monitoring residences (Casa 1 and Casa 2), as shown, are not located on a main but secondary road. However, House 2 sees a greater flow of vehicles, even on some occasions with some vehicle congestion in the area. The vehicular flow is mixed with medium-sized cargo vehicles, public transport buses, and small private vehicles. In the location of Casa 1, there is generally little vehicular activity, except for neighbour residents who come in or out with their vehicles from the indoor parking slots.

In each house the external sampling points were located on the terraces (top floor) to have more direct influx of the local winds. On the contrary, the interior points were located in the living areas of the houses. These locations were considered in strategic points to try to minimize influences by domestic activities, avoiding areas near the kitchen and preferring spaces like the bedrooms.

The following is the location of both the internal and external monitors within the houses (**Figure 4**):

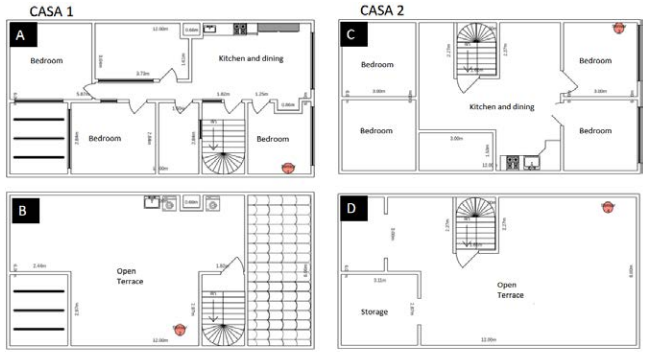

Figure 3 Sensor location **(A**) Casa 1 interior, (**B**) House 1 Terrace, (**C**) Casa 2 interior, (**D)** House 2 terrace.

2.2.2. Low-cost monitor design and construction:

The costume developed monitors work with a PMS5003T Plantower particulate matter sensor. This is a photo-optical sensor for the indirect determination of particle mass concentration. The principle of laser scattering is used by the sensor employing a laser beam that irradiates the airborne particles and then collects the scattering light to a certain degree to obtain the curve of the light change dispersion over time [19].

The sensor allows to monitor the number of particles suspended in the air at different sizes in order to infer the mass concentration assuming sphericity and a standard density of the particles. The PMS5003T sensor has the capacity to measure temperature and humidity; however, these parameters were not considered. Instead, a low-cost digital DHT11 sensor was used to monitor temperature and humidity. Each sensing node used a Nodemcu ESP 8266 card with Wifi Module that facilitated the connection and transmission of data through wireless internet connection only depending on an electrical connection.

The transmission of data and the management of the database in the Network stage was carried out using the UCAirQNET Platform [20], which allowed the consolidation of the variables information of interest and visualization in that platform.

2.2.3 Calibration of Low-Cost Monitor

Before deploying the low-cost monitor in the field, calibration was performed to evaluate its performance in comparison to a reference method. The monitor was collocated at an air quality monitoring station managed by the Secretaría de Ambiente de Bogotá. This station utilizes a beta attenuation monitor, which serves as the Reference Equivalent Method for particulate matter (PM2.5) measurement.

The calibration process followed the performance testing protocols for air sensors recommended by the U.S. Environmental Protection Agency (EPA) [21]. The evaluation focused on three key metrics: bias, linearity, and error. Bias was assessed by determining the slope and intercept (b) of the regression between the monitor and the reference method. Linearity was evaluated using the coefficient of determination (R^2), and error was quantified through the Root Mean Square Error (RMSE) and Normalized Root Mean Square Error (NRMSE).

This calibration ensured that the low-cost monitor provided reliable data for the subsequent monitoring phases and allowed comparison with the official RMCAB stations.

2.3. Phase III: Analysis of particulate matter concentration data obtained

For the analysis and **processing** of the data obtained in the field, the Anaconda Continuum Scientific Python Development Environment software (Spyder), an open software that facilitates the debugging and analysis of scientific data was used. Using descriptive statistics, the behaviour of the concentrations of indoor vs. outdoor and outdoor pollutants vs. RMCAB was evaluated. The use of the coefficient of determination of said relationships allows inferring the existing causality in the interior and exterior contamination of the residences evaluated in the Santa Cecilia neighbourhood. Such concentrations and concentration reports from RMCAB stations were compared with the relevant Colombian regulation of emission concentration for population exposure (Resolution 2254 of 2017).

3. Results and Discussion

3.1. Results of Calibration

The calibration of the low-cost monitor against a beta attenuation monitor, designated as the Reference Equivalent Method, demonstrated strong alignment with the U.S. Environmental Protection Agency (EPA) performance criteria for air sensors. The slope of the regression line between the low-cost sensor and the reference method was 0.7, which falls within the acceptable range of 1.0 ± 0.35 outlined by the EPA protocol. The intercept was 2.7 μg/m³, also within the permissible range of -5 to 5 μg/m³.
In terms of linearity, the coefficient of determination (R^2) was 0.68, slightly below the recommended threshold of 0.70 but still indicative of a strong correlation between the sensor and the reference method. Additionally, the error metrics were well within the EPA's guidelines, with a Root Mean Square Error (RMSE) of 5.74 μg/m³ (≤7 μg/m³) and a Normalized Root Mean Square Error (NRMSE) of 10.7% (≤30%).
These results validate the suitability of the single low-cost monitor for PM2.5 measurements, particularly in terms of bias and error performance. The alignment with the EPA's criteria highlights the sensor's potential for deployment in localized air quality studies, especially in resource-limited settings. While there is slight room for improvement in linearity, the sensor demonstrated reliable performance, making it a cost-effective tool for enhancing air quality monitoring efforts.
Despite the strong alignment of the low-cost monitor with the Reference Equivalent Method and its promising performance, it is important to consider some limitations inherent to low-cost sensors. Over time, the precision of these sensors can decrease due to the accumulation of dust on the laser component, which may lead to inaccurate measurements if not cleaned or maintained properly. Additionally, these sensors are sensitive to conditions of high humidity, which can interfere with the accuracy of particulate matter data by causing overestimations due to water particle deposition. These limitations highlight the importance of regular maintenance, such as cleaning the sensor's laser, and avoiding deployments in environments with persistently high humidity levels unless proper protective measures are taken. To ensure the continued reliability and accuracy of measurements, it is essential to perform frequent and periodic calibration processes, comparing the low-cost sensors with reference-grade instruments. This approach mitigates the potential decline in performance over time and ensures the data remains robust for long-term monitoring efforts.

3.2. Data processing and analysis for in situ measurements

Between October 19, the day the pilot tests began, and October 24, modifications and adjustments were performed to evaluate the behaviour of the sensors and the data transmission to UCAirQNet. During the monitoring phase, technical failures occurred in two sensors, particularly the internal monitor in Casa 1. These failures were attributed to programming issues that prevented data transmission, highlighting opportunities for improvement in these custom technologies, which are still in the validation phase. On the other hand, the external monitor in Casa 2 only reported concentrations until October 29 and no more signals were received thereafter, resulting in no data for the following two sampling days.

The mass concentration data collected during the testing and monitoring phase for the 3 monitors that were in operation are displayed below. **Figure 5A** shows the behaviour of the three variables monitored by the Casa1_out sensor, which was one of the most stable units in terms of technical performance.

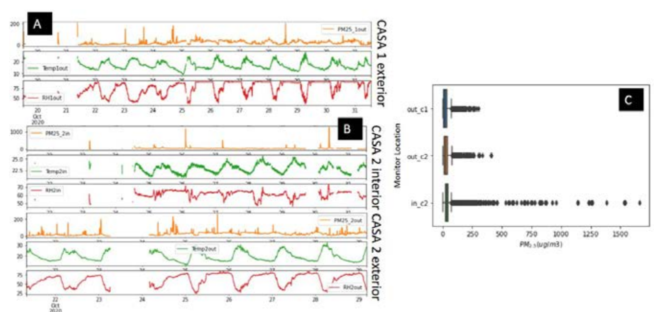

Figure 4 Particulate Matter concentrations, RH and temperature measured **(A)** Casa 1, **(B)** Casa2, **(C)** Box plot figures of PM2.5 concentration distributions in Casa 1 y Casa 2.

Figure 5B shows the behaviour of the same variables in the other two monitors implemented in Casa 2. PM2.5 exterior concentration displays a more irregular behaviour than those in the interior, as is seen with the multiple peaks for each curve.

Between RH and temperature in all cases there is an inverse relationship as it is expected. It is also visible that for the highest peaks of $PM_{2.5}$ concentrations relative humidity had also maximum values. This could be related to a greater deposition of water onto the detected particles, which translates into a greater particle volume measured by the PMS sensors.

When comparing the concentration distributions for all three monitors, outside PM2.5 concentrations present a very similar distribution; however, the monitor installed inside casa 2 presents a large number of outliers. This may be due to domestic activities carried out inside the house promoting out of normal concentrations (**Figure 5C**).

A more detailed analysis for the internal sensor concentrations for house 2 shows very high $PM_{2.5}$ concentration peaks reaching a maximum of 1661 ug/m^3 (**Table 1**), with a standard deviation of 73.94 µg/m^3.

Table 1 Dispersion statistics of PM concentration

Sampling Point	M concentration (ug/m^3)

	Max	**Min**	**Mean**	**SD**
Casa 1 outside	300	1	23,5	18,99
Casa 2 outside	414	1	26,97	24,12
Casa 2 inside	1661	1	44,06	73,94
RMCAB Suba	43	0	13,33	8,2
RMCAB Bolivia	43,1	1,9	18,19	8,25

It is worth mentioning here again that at Casa 2 sampling point there is a greater vehicular flow daily. This activity could affect the concentrations of PM and increase them.

In the case of the external sensors, a different behaviour is found. Since they are located on the terrace, the domestic emissions did not affect them the same way as the internal sensor. Here, concentration peaks of up to 414 ug/m³ in Casa 2 and 300 ug/m³ in Casa 1 were found, which are relatively low compared to the inside monitor reports. Concentrations found outside are less disperse with a lower standard deviation of 24.12 ug/m³ and 18.88 ug/m³, respectively.

As for the relation in concentrations of the internal and external sensors at Casa 2, a low correlation was found (**Figure 6**). According to the coefficient of determination estimated to be less than 3%, the variations in PM concentrations outside have little or no influence on the behaviour of PM2.5 inside the residence 2.

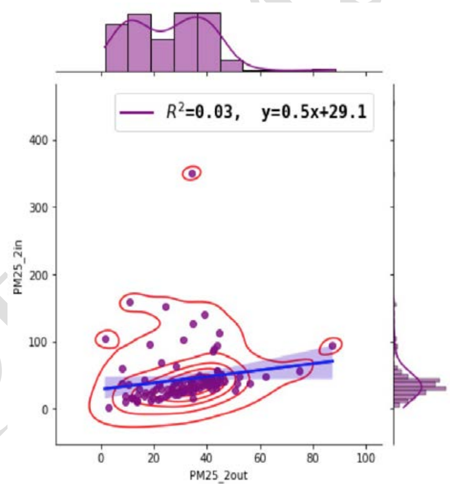

Figure 5 Dispersion plot of outdoor Casa 2 PM2.5 concentration vs Indoors

Based on the intercept found in the regression, even with the total removal of the fine material outdoors, a high concentration of about 29.1 ug/m3 would be expected indoors. Therefore, it could be inferred that the concentrations inside these residences could be more directly attributed to the activities performed indoors.

3.2. Analysis for outdoor and external measurements

Regarding the outdoor concentrations of Casa 1 and Casa 2, it is possible to identify that in the latter there are more activities that affect the air quality, which we associate to the heavier traffic around. There is no direct source of vehicular circulation and other emissions that could increase concentrations for Casa 1. **Figure 7A** displays these concentrations as a function of the sampling time, confirming the possible influence of these very close point emissions.

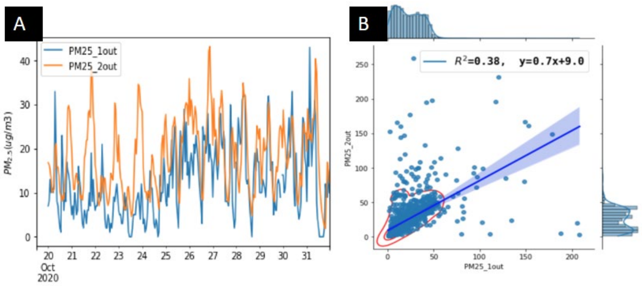

Figure 6 Temporal behaviour of PM2.5 outside Casas 1 and 2

By comparing the behaviour of the external sensors, it is possible to identify similar patterns such as the bimodal concentrations of PM2.5 in both cases. When evaluating the correlation of these two data series, a Determination coefficient R2 = 0.38 was found (**Figure 7B**).

With respect to the particulate matter reports given by the RMCAB, **Figure 8** presents the concentrations of PM2.5 for the Suba and Bolivia stations in the evaluated time range. A great difference is observed in terms of the concentration of PM2.5 at both places. Although the concentration reports from these stations are from reference instruments (Beta attenuation) managed by the Secretary of Environment of the city, it is evident that the correlation in the concentrations is not significant with an R^2 of only 26%. This behaviour can be influenced by meteorological factors and from different nearby emission sources.

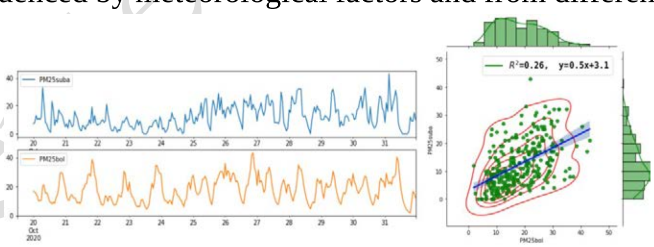

Figure 7 PM2.5 Concentrations from the RMCAB, stations Bolivia and Suba [ug/m3]

Given that the Bolivia station is located closer to the analysed neighbourhood, it was used to compare with the PM2.5 concentrations measured outdoors using our low-cost sensors. We identified that there is a null correlation, with an R^2 of 0%. Despite the proximity, this result would indicate that the RMCAB reports would not be valid or indicative for the population settled in the Santa Cecilia neighbourhood. The predominant directions of the wind currents (blowing_from) for the Las Ferias and Suba stations were constructed with a diameter of 3 km to better demonstrate their behaviour. It is possible to observe that the Las Ferias station presents predominant winds from the west direction (**Figure 9**), relating this behaviour with the winds towards the area of interest. Here a little interaction of winds in a north-westerly direction is observed with a low speed between approximately 0.5 to 2.1 m / s, which would indicate its little correlation with the air currents directed from the industrial zone.

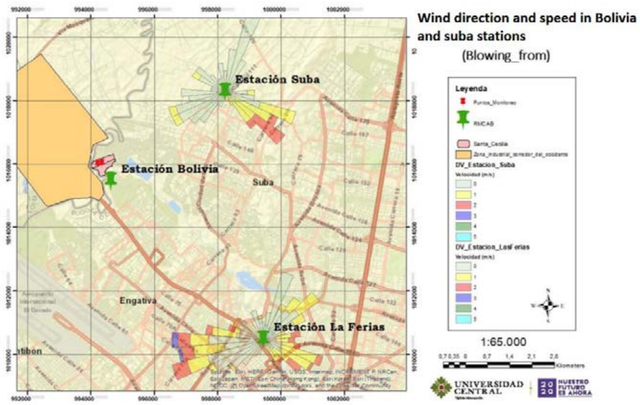

Figure 8. Wind direction and speed (blowing_from) of the RMCAB stations closest to the study area

In contrast, at the Suba station, located approximately 4.8 km from the Santa Cecilia neighbourhood, the dominant wind direction is towards the north with relatively low speed. This suggests a greater interaction with the area of interest. Specifically, wind currents are prevalent from the southwest, originating from the study area. This indicates a potential interaction of wind currents from the western corridor towards the Santa Cecilia neighbourhood (**Figure 9**). Therefore, even though there may be relevant emissions from the industrial hub along the 80 highway, the prevalent direction of the wind transport is not dragging the pollutant into the Santa Cecilia neighbourhood but rather to a different location that will require further studies. Thus, the concentration of fine particulate matter within the residences are more related to indoor house activities or nearby vehicle circulation. Ventilation measures are recommended to ensure that during cooking or cleaning activities PM concentrations do not reach extreme levels.

Building on these findings, similar studies such as [22] highlight the dynamic interplay between indoor and outdoor air quality. Their work demonstrated that indoor PM2.5 concentrations are significantly influenced by the timing and intensity of indoor activities as well as outdoor air infiltration. For example, peak concentrations were often observed during cooking events, corroborating the results presented in this study. Furthermore, [22] emphasizes the importance of understanding the temporal variability of PM2.5 to optimize indoor ventilation strategies and reduce exposure.

The implications of these findings suggest that ventilation timing should be carefully managed to coincide with periods of lower outdoor pollution, thus minimizing pollutant ingress while still reducing indoor pollutant accumulation. For residences in areas like the Santa Cecilia neighbourhood, where nearby vehicle traffic can contribute to outdoor PM2.5, advanced air quality monitoring systems, such as networks of low-cost sensors, could inform real-time ventilation decisions.

Additionally, [22] points to the potential benefits of community-based air quality interventions. For instance, targeted educational campaigns could help residents understand the sources and impacts of indoor air pollution and encourage practical actions such as using exhaust fans during cooking or reducing dust accumulation through regular cleaning. Policymakers could support such initiatives by subsidizing low-cost sensors for residential use, thereby empowering communities to monitor and address their air quality challenges.

Ultimately, these complementary insights reinforce the importance of integrating localized air quality monitoring with actionable strategies to mitigate indoor air pollution. Future studies could expand on this work by exploring year-round variations in PM2.5 concentrations, incorporating the influence of seasonal meteorological patterns, and examining the effectiveness of proposed ventilation measures in diverse housing environments.

4. Conclusions

Based on the data obtained and analysed using our custom-built low-cost sensors, we conclude that fine particulate matter (PM2.5) concentrations in the interiors of the Santa Cecilia neighbourhood are predominantly influenced by indoor activities, such as cooking, cleaning, and the use of household products. Only 3% of the indoor concentrations were found to relate to external sources or influxes. However, outdoor activities, particularly vehicle traffic near the residences, remain relevant factors when addressing indoor air pollution, as they can contribute to elevated pollutant levels. This underscores the importance of planning ventilation times during periods of low outdoor pollution to minimize PM infiltration indoors.

The concentrations of PM2.5 attributable to the industrial zone along the 80th highway were found to depend heavily on wind direction, which predominantly flows westward and, in some cases, south-eastward. Although community concerns about health impacts from the industrial hub are valid, this study concludes that its influence on the Santa Cecilia neighbourhood is relatively low. Residents can mitigate indoor air pollution by adopting simple measures, such as strategic natural ventilation and the use of exhaust systems during indoor activities.

Additionally, insights from recent literature emphasize the need for community-based interventions to enhance public awareness about indoor air quality and empower residents with affordable monitoring tools. Subsidizing low-cost sensors and integrating them into real-time monitoring systems could help address localized air quality challenges effectively.

Finally, while our custom-designed low-cost sensors demonstrated the capability to monitor PM2.5 concentrations in real time, their performance is subject to limitations, such as sensitivity to high humidity and the need for regular maintenance and calibration. Further technological advancements are necessary to improve the long-term stability and accuracy of these devices, especially for extended monitoring campaigns. These improvements, coupled with broader studies that account for seasonal variations and meteorological influences, could provide a more comprehensive understanding of indoor-outdoor air quality interactions in urban settings.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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Author contributions

All authors contributed to the study conception and design. Material preparation and data collection: Y. Salinas, C. Reyes, and S. Becerra. The data analysis: Yisel. A. Vargas, Adriana. K. Toro, and Oscar. A. Fajardo. The final draft of the manuscript: Yisel. A. Vargas, Adriana. K. Toro, and Oscar. A. Fajardo, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. Data was collected using a custom-made monitor using a photo-optical sensor for particulate matter as described in the methodology, during October 2020 in the Santa Cecilia neighbourhood of Bogotá, Colombia.

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