Brazilian Journal of Analytical Chemistry
Pre-publication – Accepted after peer review
doi: 10.30744/brjac.2179-3425.AR-59-2025

BrJAC

ARTICLE

Low-Cost Particulate Matter Sensor in Indoor and External Classroom Environments

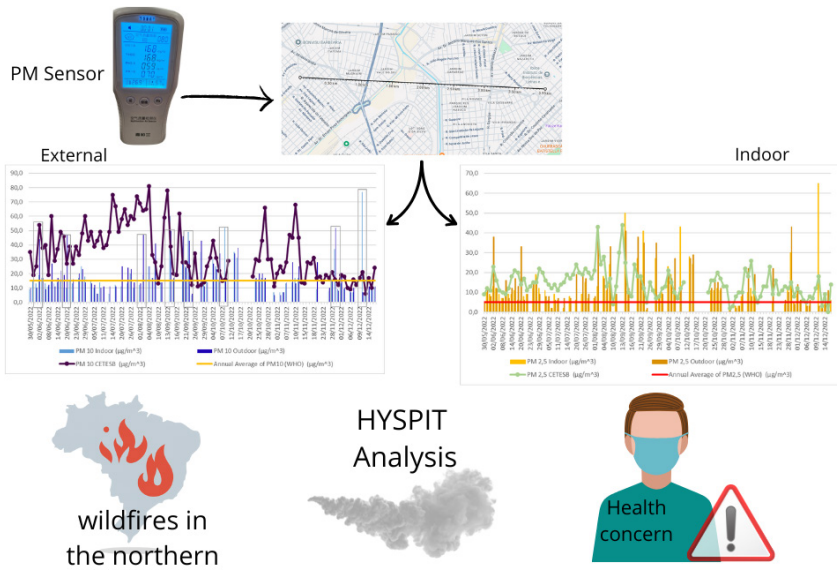
José Henrique De Souza Fernandes[1]*, Leonardo Marques Alves Ribeiro[2], Iêda Aparecida Pastre[3], Cristina Maria Roque Ramiro de Oliveira[4], Fernando Luís Fertonani[3]

[1]*Departamento de Metrologia, Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio). Rua Marquês de São Vicente, 225, Gávea, Rio de Janeiro, RJ 22451-900, Brazil*

[2]*Instituto de Química, Universidade de São Paulo (IQ-USP), Laboratório de Sensores Eletroquímicos e Métodos Eletroanalíticos (LSEME). Avenida Professor Lineu Prestes, 748, Cidade Universitária, São Paulo, SP 05508-000, Brazil*

[3]*Departamento de Química e Ciências Ambientais, Universidade Estadual Paulista (UNESP), Instituto de Biociências, Letras e Ciências Exatas (Ibilce). Rua Cristóvão Colombo, 2265, Jardim Nazareth, São José do Rio Preto, SP 15054-000, Brazil*

[4]*Departamento de Química e Bioquímica, Faculdade de Ciências, Universidade de Lisboa (FCUL). Campo Grande, 1749-016, Lisboa, Portugal*



This study evaluates the concentrations of particulate matter (PM_{10} and $PM_{2.5}$) in indoor and outdoor university classrooms using a low-cost particulate matter sensor. Measurements were conducted hourly, daily, and annually in a closed, air-conditioned classroom at the Institute of Biosciences, Letters and Exact Sciences (Ibilce) of São Paulo State University (UNESP) throughout 2022. Results revealed that PM_{10} levels consistently exceeded the World Health Organization's (WHO) annual guideline of 15 μg m^{-3}, aligning with local CETESB data. Meanwhile, average indoor $PM_{2.5}$ concentrations (12.5 ± 11.2 μg m^{-3}) were almost three times the annual WHO limit of 5 μg m^{-3}. Peak values reached 43.75 μg m^{-3}, nearly 900% above the guideline, raising significant health concerns, and the calculated hazard quotient (HQ) approached the reference threshold. Outdoor $PM_{2.5}$ concentrations showed similar trends, with multiple peaks surpassing recommended thresholds. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) analysis linked high

Cite: Fernandes, J. H. S.; Ribeiro, L. M. A.; Pastre, I. A.; de Oliveira, C. M. R. R.; Fertonani, F. L. Low-Cost Particulate Matter Sensor in Indoor and External Classroom Environments. *Braz. J. Anal. Chem.* (Forthcoming). http://dx.doi.org/10.30744/brjac.2179-3425.AR-59-2025

Submitted: July 7, 2025; **Revised:** October 4, 2025; November 6, 2025; November 19, 2025; **Accepted:** November 28, 2025; **Published online:** January 2026.

This article is part of the BrJAC Special Issue on the 8th Uruguayan Congress of Analytical Chemistry (CUQA 8 2024).

PM levels to wildfires in central and northern Brazil and localized factors, including vehicle traffic and classroom maintenance. Statistical analysis revealed no significant difference between indoor and outdoor $PM_{2.5}$ levels, emphasizing the influence of external pollution on indoor air quality. These findings show the urgency of implementing targeted interventions, such as regular cleaning of classrooms, curtains, and air conditioning systems, to mitigate PM exposure. The study highlights the need for improved air quality management to ensure a safe learning environment for students and faculty.

Keywords: environmental chemistry, HYSPLIT, indoor air quality, low-cost sensor, $PM_{2.5}$ concentration

INTRODUCTION

Air quality is directly linked to the concentration and size of particulate matter (PM) in the atmosphere. According to the World Health Organization (WHO), in 2019, almost seven million premature deaths worldwide (accounting for almost 12% of all deaths)[1] were partially attributed to poor air quality, compromised by high levels of atmospheric PM.[2]

The term “aerosol” was introduced by Schmauss in 1920 to describe particles that remain suspended in the air with high stability, particularly those smaller than 100 µm in diameter.[3] Aerosols can exist in both solid and liquid states. For many years, the atmospheric particle standards of numerous countries were based on the measurement of the mass concentration of “Total Suspended Particles” (TSP). However, since TSP often includes non-inhalable particles that have a lesser impact on respiratory and cardiovascular diseases, there was no clear correlation between TSP levels and health effects.[4]

PM is categorized by size into coarse particles (PM_{10}), fine particles ($PM_{2.5}$), and ultrafine particles (less than 0.1 µm). PM is further classified by its emission sources, categorized as primary (natural sources such as volcanic activity, forest fires, sea spray) or secondary (anthropogenic sources, including particles formed through nucleation, condensation of gaseous components, and chemical and photochemical reactions in the atmosphere). Secondary aerosols are divided into four major groups: sulphate aerosols, nitrate aerosols, Cl-aerosols and secondary organic aerosols, with secondary anthropogenic fine particles having a significant impact on human health.[5]

In indoor environments, concerns about air quality became prominent in the 1970s with the trend of constructing sealed buildings for acoustic insulation, climate control, aesthetics, and security. This led to an increase in health issues related to indoor air quality.[6] Poor indoor air quality is mainly caused by inadequate cleaning of air conditioning systems, recirculation of air, and a lack of periodic control over potential sources of contamination.[7] The fine fraction of indoor air typically contains a mixture of particles from combustion processes and secondary particles generated by atmospheric chemical reactions, including acid condensates, sulphates, and nitrates.[8] $PM_{2.5}$ particles, in particular, can adsorb and carry high concentrations of mutagenic substances, such as polycyclic aromatic hydrocarbons (PAHs), which are predominantly concentrated in $PM_{2.5}$.[9]

Beyond direct health effects, aerosols have significant economic impacts,[10] and exposure to these particles is associated with cardiovascular diseases,[11,12] pulmonary inflammation,[13] bronchitis, asthma, and other respiratory conditions,[14] lung cancer,[15] and an increased risk of diabetes due to exposure to $PM_{2.5\text{-}0.1}$.[16,17] Additionally, these particles can impair cognitive function in individuals exposed to them in closed, climate-controlled environments,[18] with increased carbon dioxide (CO_2) levels further reducing concentration and cognitive abilities. This study aims to assess the concentration of PM_{10} and $PM_{2.5}$ in both indoor (closed and air-conditioned classrooms) and outdoor university environments, with a focus on the impact of exposure over time.

While indoor air quality has been extensively studied in residential and commercial buildings,[19,20] university classrooms remain underrepresented in the literature. Despite advances in understanding PM dynamics, the complexity of factors influencing indoor pollutant concentrations such as outdoor PM infiltration[21] and human activity-driven particle resuspension[22] remains poorly characterized in educational environments. This gap is particularly critical in classrooms, where prolonged student occupancy and climate-controlled conditions

may amplify exposure risks. By investigating the emission of these PMs on closed indoor classrooms, this study seeks to contribute to assess the exposure of students to PM in these settings.

MATERIALS AND METHODS

Sensor configuration

The sensor used in this study was a commercially available portable multiparameter air quality sensor (version 2.03) equipped with a PMS5003 sensor, suitable for measuring PM with diameters up to 10 μm. The measurements were divided between coarse (10 μm to 2.5 μm) and fine particles (2.5 μm to greater or equal than 1.0 μm). Although the sensor is sensitive to particles with diameters below 1.0 μm, the ultrafine particle fraction was not explicitly reported by the air quality sensor. According to the manufacturer, the reported maximum errors are ±10 μg m^{-3} in the concentration range 0–100 μg m^{-3} range, and ±10 % in the range of 100–500 μg m^{-3}. The device was factory-calibrated following the manufacturer's specifications. This sensor employs a light-scattering approach to measure $PM_{2.5}$, and PM_{10} mass concentrations in real-time with a total response time of about 10 seconds.

Additionally, it was equipped with a DHT11 module to monitor temperature and humidity. The DHT11 is a digital sensor capable of measuring temperature in the range of -40 to 80 °C with an accuracy of ±0.5 °C and relative humidity from 0 to 100% with an accuracy of ±2-5%. This combination allows the sensor to provide comprehensive environmental data, offering insights into both PM and ambient conditions, crucial for assessing air quality in indoor and external environments.

The PM values displayed on the sensor screen were manually transcribed during classes and subsequently digitized into an Excel spreadsheet to enable systematic analysis and comparison with reference data.

Sensor sampling

Measurements were conducted with a single sensor on each weekday when classes were held, with a minimum of eight indoor measurements per day. Additionally, outdoor measurements were taken every two hours to map the concentration of PM on days when the spaces were in use, as is shown in Table I. This systematic monitoring primarily focused on the C block at the Institute of Biosciences, Letters and Exact Sciences of São Paulo State University (UNESP-Ibilce), which was selected because it hosted most of the chemistry, mathematics, and physics classes (Lat: -20.785402, Long: -49.360823), providing a detailed assessment of PM concentrations in both indoor and outdoor environments during active periods.

Table I. Sampling plan for 2022

	1st Semester of 2022					2nd Semester of 2022				
Schedule	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**
8 a.m.	ID	ID	ID	ID		ID	ID	ID	ID	
9 a.m.	ID	ID	ID	ID		ID	ID	ID	ID	
10 a.m.	OD	OD	OD	OD		OD	OD	OD	OD	
10:10 a.m.	ID	ID	ID	ID		ID	ID	ID	ID	
11 a.m.	ID	ID		ID		ID	ID		ID	
12 p.m.	OD	OD	OD	OD		OD	OD	OD	OD	
12:10 p.m.	ID	ID	ID	ID		ID	ID	ID	ID	
1 p.m.										
2 p.m.	OD	OD	OD	OD		OD	OD	OD	OD	

(continued on next page)

Table I. Sampling plan for 2022 (continued)

	1st Semester of 2022					2nd Semester of 2022				
Schedule	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**
2:10 p.m.	ID	ID	ID			ID	ID	ID		
3 p.m.	ID	ID	ID			ID	ID	ID		
4 p.m.	OD	OD	OD	OD		OD	OD	OD	OD	
4:10 p.m.	ID	ID	ID			ID	ID	ID		
5 p.m.		ID	ID				ID	ID		
6 p.m.		ID	ID				ID	ID		
6:10 p.m.	OD	OD	OD			OD	OD	OD		
7 p.m.		ID	ID				ID	ID		

ID: Indoor sampling; OD: outdoor sampling.

All measurements were conducted at a height of 120 cm from the ground, approximately at the average seated nose height, and positioned at the center of the classroom. During measurements, the door was kept closed, and the air conditioner was operating to maintain consistent indoor conditions. The data collection aimed to capture the presence and behavior of PM across three different temporal scales: hourly, daily, and annually. This was achieved by calculating the mean PM concentration for each day, providing a comprehensive analysis of PM variations over time.

The measurements were taken during class sessions because the primary objective was to assess the actual exposure of students to PM. By measuring in the occupied classroom, we capture the effects of human activity and occupancy on indoor air quality, which directly reflects the environment that students experience.

Environmental Company of the State of São Paulo (CETESB) comparison

To benchmark classroom PM measurements against the ambient urban air, we incorporated data from a nearby CETESB monitoring station. The specific sensor model used by CETESB is not disclosed. The station is operated by the state government environmental agency and is located at Lat: -20.784862, Long: -49.398324. The station continuously records hourly PM concentrations and serves as a proxy for the city's overall air quality. In our methodology, we aligned the temporal resolution of our classroom measurements with CETESB's hourly data, ensuring consistency in comparison. This approach allows us to assess student exposure within the classroom relative to the broader urban environment. Figure 1 displays a Google Maps view depicting the spatial relationship between the UNESP campus and the CETESB station. Notably, the map shows that the CETESB station is located at a significant distance from UNESP and is situated in an area surrounded by several high-pollution sources, such as major roads and industrial zones. This geographical context suggests that the higher average PM levels recorded by CETESB may be influenced by these external sources, thereby providing a meaningful benchmark for comparing indoor and urban air quality.

Figure 1. Distance between C-block-UNESP and CETESB station.

Retro-trajectory HYSPLIT

HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) is a widely used atmospheric modeling tool developed by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory.[23-26] NOAA is the primary U.S. federal agency for monitoring and researching atmospheric and oceanic processes, and its models are internationally recognized for applications in air quality and climate studies. HYSPLIT simulates the dispersion and trajectory of particles in the atmosphere using a Lagrangian framework, where an air parcel is tracked as it moves through space. This approach calculates advection and diffusion separately, driven by meteorological data from numerical weather prediction models such as the Global Forecast System (GFS).

In this study, twelve days of retro-trajectories were simulated throughout 2022 over the C block of UNESP, resulting in a total of 36 retro-trajectories at three different altitudes: 500 m, 1000 m, and 1500 m.

Health risk assessment

To estimate the potential health impacts associated with exposure to particulate matter (PM), a quantitative health risk assessment was conducted based on the mean concentrations obtained for both $PM_{2.5}$ and PM_{10}. The calculation considered the following parameters: inhalation rate (IR) ($m^3 \times day^{-1}$), exposure time (ET) ($hours \times day^{-1}$), exposure frequency (EF) ($\text{days} \times year^{-1}$), exposure duration (ED) ($year$), body weight (BW) (kg), and averaging time (AT) (days). These parameters were integrated to determine the Average Daily Dose (ADD) ($\text{mg} \times \text{kg}^{-1} \times \text{day}^{-1}$), according to Equation (1).[27]

$$ADD = {C_{air}\ x\ IRx\ ETx\ EFx\ ED}/{BW\ x\ AT} \qquad \text{Equation (1)}$$

Where C_{air} is the mean particulate concentration in the air ($mg \times m^{-3}$).The values adopted for IR and BW were obtained from the Environmental Protection Agency (EPA)[28] (21 to <31 years old) and Centers for Disease Control and Prevention (CDC),[29] respectively.

Subsequently, the Lifetime Excess Cancer Risk (ELCR) was calculated to evaluate potential carcinogenic effects during the period of university attendance, assumed to be four years. The ELCR was derived from the ADD and the slope factor (SF), as described in Equation (2).[30]

$$\mathrm{ELCR} = \mathrm{ADD} \times \mathrm{SF} \qquad \text{Equation (2)}$$

In this context, the slope carcinogenic potency factor (SF) was obtained from the literature.[31] It is important to note that, given the well-established evidence that PM_{10} exhibits less detrimental health effects compared to $PM_{2.5}$, only $PM_{2.5}$ concentrations were considered for the carcinogenic risk assessment.

In addition, the Hazard Quotient (HQ) was calculated for both $PM_{2.5}$ and PM_{10} to estimate potential non-carcinogenic risks, as expressed in Equation (3).[32]

$$\mathrm{HQ\ (hazard\ quotient)} = {}^{\mathrm{ADD}}/_{\mathrm{RfD}} \qquad \text{Equation (3)}$$

Where ADD corresponds to the average daily dose and RfD is the reference dose. The RfD was estimated from the inhalation reference concentrations (RfC) established by the WHO, with values of 5 μg m^{-3} for $PM_{2.5}$ and 15 μg m^{-3} for PM_{10}, as shown in Equation (4):

$$\mathrm{RfD} = {}^{\mathrm{RfC} \times \mathrm{IR}}/_{\mathrm{BW}} \qquad \text{Equation (4)}$$

According to international guidelines, HQ values greater than 1 indicate potential non-carcinogenic risks of concern, requiring preventive or corrective actions. Conversely, HQ values below 1 are generally considered within acceptable limits of exposure.[33]

RESULTS AND DISCUSSION

The following represent the complete sampling/measurement periods in a broader context. The measurement values, specifically the daily averages of PM_{10} and $PM_{2.5}$, were compared against the WHO limits and the data provided by the local CETESB station for the same period.

Hourly behavior of PM inside classrooms

During the afternoon of August 2, 2022, measurements of PM_{10} and $PM_{2.5}$ were conducted inside active classrooms to assess PM levels and their behavior. Figures 2 and 3 present the results of these measurements over a 60-minute period, with data sampled approximately every 5 minutes. Both PM_{10} and $PM_{2.5}$ concentrations displayed similar trends throughout the 60-minute period, with PM_{10} values consistently higher than those of $PM_{2.5}$.

The average concentration of $PM_{2.5}$ measured indoors was approximately 6.92 ± 0.92 μg m^{-3} (or 6.92 ± 13.6%), remaining below the 24-hour limit of 15 μg m^{-3} recommended by the WHO.[2] However, if this average is extrapolated for the hole year compared to the annual limit of 5 μg m^{-3}, it exceeds the threshold, indicating a potential long-term exposure risk. Conversely, the average PM_{10} concentration indoors was 11.42 ± 1.49 μg m^{-3} (or 11.42 ± 13.0%), staying below both the WHO's 24-hour limit of 45 μg m^{-3} and the annual limit of 15 μg m^{-3} if the value is extrapolated, suggesting compliance with air quality standards for this pollutant.

A key observation from these data is the relative consistency in individual measurements, with variations close to 10%, which indicates a stable indoor air quality environment during the period of observation. Based on this finding, the monitoring strategy was adjusted to be conducted on an hourly basis. The rationale for this decision is that preliminary comparisons among different measurement intervals (every 10 minutes, every 30 minutes, and every hour) did not reveal substantial short-term fluctuations that would justify higher-frequency sampling. Thus, adopting hourly measurements still capture representative variations in PM concentrations throughout the observation period. This approach allowed the data to consistently reflect the ongoing indoor conditions without unnecessary redundancy in sampling.

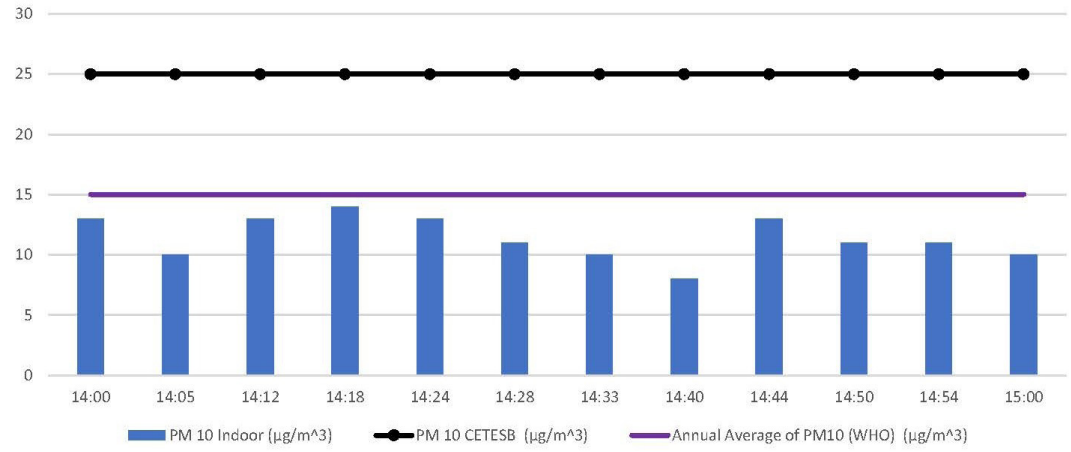


Figure 2. PM_{10} concentration in an active classroom environment, measured every 5 minutes, compared to CETESB data.

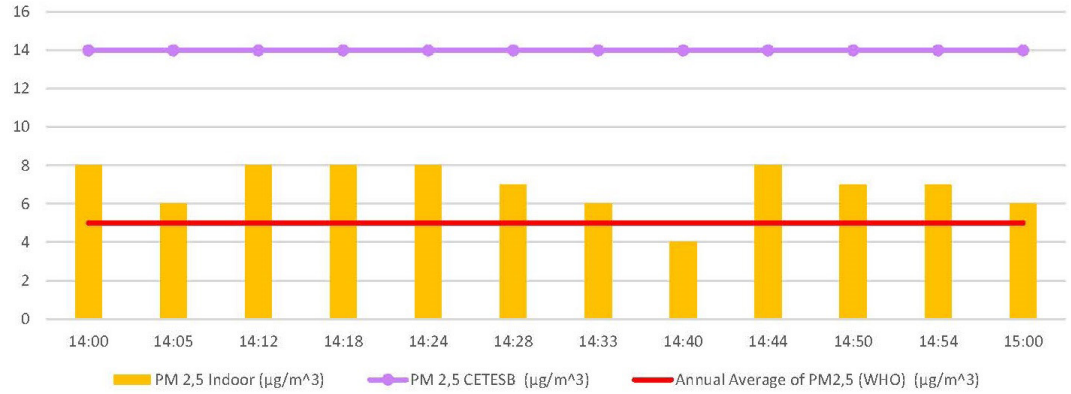


Figure 3. $PM_{2.5}$ concentration in an active classroom environment, measured every 5 minutes, compared to CETESB data.

Daily behavior of PM inside classrooms

On May 31, 2022, PM_{10} and $PM_{2.5}$ sampling and measurements were conducted at consistent 60-minute intervals, as illustrated in Figures 4 and 5, excluding the period allocated for lunch. These measurements aimed to evaluate the behavior of PM throughout a day of academic activities.

Analysis of Figure 5 reveals a significant trend at the commencement of classes, where $PM_{2.5}$ concentrations approached the WHO recommended limit for 24 hours. This increase is likely attributable to the influx of individuals into the classrooms, the movement of curtains, and the activation of fans in conjunction with the air conditioning systems. Subsequently, $PM_{2.5}$ levels decrease as students remain stationary during instructional periods. A minimum concentration was observed at 10:00 a.m., corresponding with the recess period, after which $PM_{2.5}$ levels rise again due to the re-entry of students into the classrooms.

This pattern is consistently observed during the afternoon session, external classroom measurements exhibit similar trends to the internal measurements, with internal values remaining near the WHO recommended limits for 24 hours, which may adversely affect teaching activities. Internal PM_{10} concentrations, as shown in Figure 4, follow a pattern analogous to $PM_{2.5}$, with concentrations decreasing between 6:00 a.m. and 11:00 a.m., reaching a minimum at 9:00 a.m., and decreasing again after 5:00 p.m. External $PM_{2.5}$ measurements occasionally exceeded CETESB values between 8:00 a.m. and 3:00 p.m.

This observed behavior is likely a consequence of vehicular traffic both within the campus (parking lot) and on adjacent public roads, as well as intra-campus activities performed by general services. However, $PM_{2.5}$ concentrations decrease relative to CETESB data from 4:00 p.m. to 6:00 p.m., coinciding with the cessation of general services activities. In contrast, external PM_{10} concentrations generally parallel CETESB data, except during the period from 12:00 p.m. to 2:00 p.m., when local measurements exceed CETESB values due to increased traffic of cars and motorcycles in the parking area and public roads.

Overall, the data indicate that PM levels inside and outside the classrooms are influenced by both internal campus activities and external traffic patterns. The proximity of internal $PM_{2.5}$ measurements to WHO limits underscores the necessity for effective air quality management strategies to maintain a conducive learning environment.

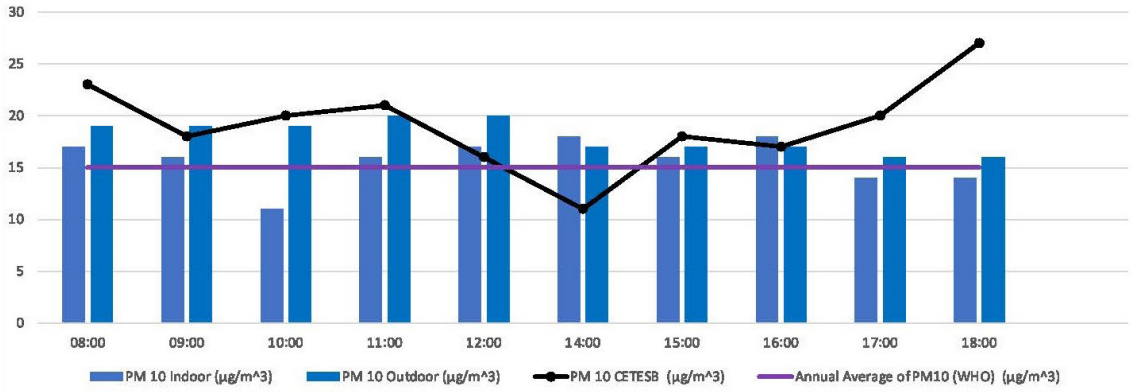


Figure 4. Concentration of PM_{10} measurements (Indoor/Outdoor) obtained at 60-minute intervals, compared with CETESB values on 2022-05-31.

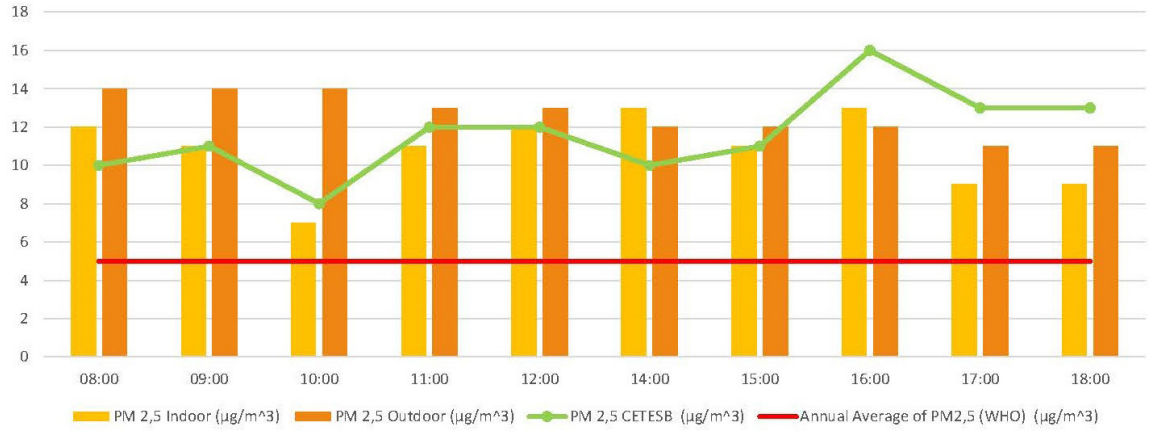


Figure 5. Concentration of $PM_{2.5}$ measurements (Indoor/Outdoor) obtained at 60-minute intervals, compared with CETESB values on 2022-05-31.

Yearly behavior of PM inside classrooms

Throughout 2022, systematic sampling and measurements of PM_{10} and $PM_{2.5}$ concentrations were conducted both inside and outside the classrooms. The results over the course of the year are presented in Figures 6 and 7, which illustrate the temporal evolution of PM concentrations during 2022. The data show that, for the most part, PM_{10} and $PM_{2.5}$ concentrations, both indoors and outdoors, remained well above the WHO's recommended thresholds of 15 µg m^{-3} and 5 µg m^{-3}, respectively. Furthermore, it is evident that the data from CETESB and the measurements taken inside the classrooms follow a similar pattern.

Exceptions to this trend are highlighted in orange rectangles in Figures 6 and 7. These anomalies are likely due to sporadic rainfall during the second semester, which led to periods of higher humidity and warmer conditions, resulting in atypical concentration levels during the study period.

The outliers observed at the end of the year, specifically on 2022-11-28 and 2022-12-12, were traced back to specific events. These included maintenance activities near the classrooms, such as grass cutting and sweeping with specialized equipment and manual blowers, as well as the release of chalk dust from careless eraser cleaning within the classroom environment.

Regarding CETESB's monitoring during the same period, several intense peaks in PM_{10} and $PM_{2.5}$ were recorded, all exceeding WHO guidelines. These discrepancies between the study's findings and CETESB's data can be explained by the geographical location of the CETESB station, which is near a busy highway. The increased vehicular traffic and lack of adequate tree cover likely contributed to these peaks.

Notably, during the first semester, the PM_{10} and $PM_{2.5}$ concentrations recorded by CETESB were significantly higher than those observed in the classrooms. Conversely, in the second semester, this trend reversed. This inversion may be attributed to temperature variations, as May to July are characterized by colder temperatures, with chilly mornings and evenings. The presence of trees, as previously mentioned, helps reduce temperature and acts as a barrier to PM, contributing to lower PM concentrations in the atmosphere.

As observed in Figures 6 and 7, there are some data gaps in CETESB's records. These gaps are due to maintenance issues in CETESB's data collection and measurement systems, which prevented the availability of PM_{10} and $PM_{2.5}$ data for certain days.

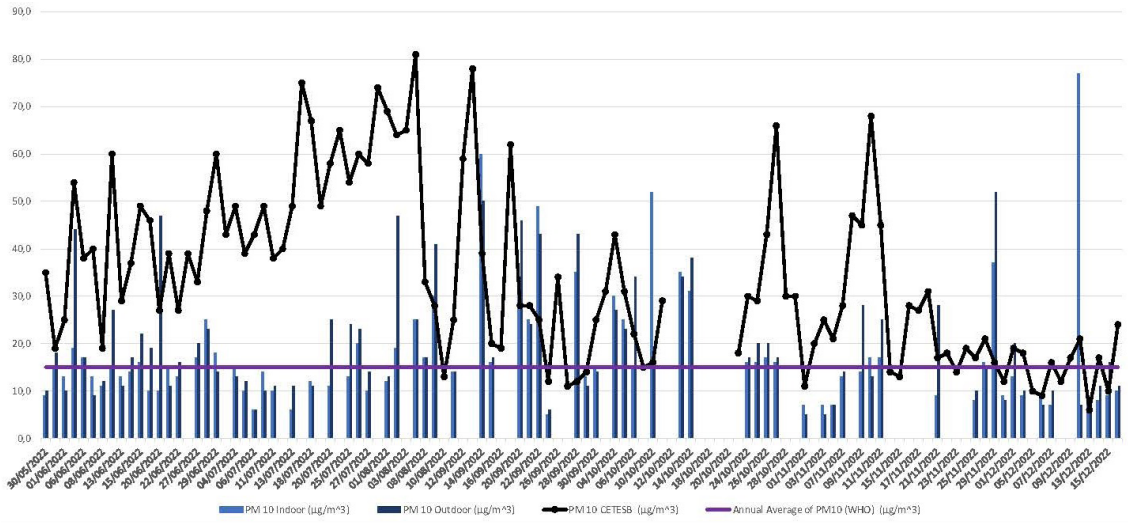


Figure 6. Average concentrations of PM_{10} for the year 2022, both outside and inside classrooms, compared with CETESB data.

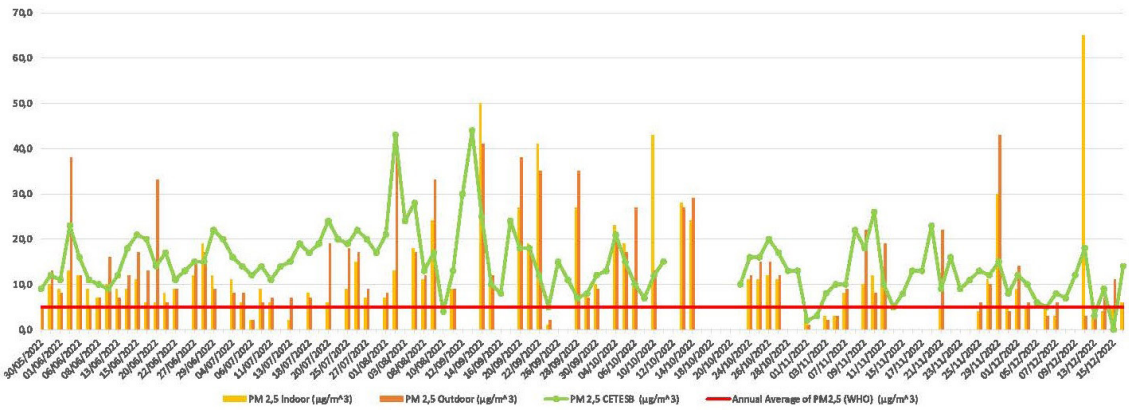


Figure 7. Average concentrations of $PM_{2.5}$ for the year 2022, both outside and inside classrooms, compared with CETESB data.

The annual data collected in this study, along with the measurements provided by CETESB's monitoring station, analyzed using a paired-sample *t*-test (df = 72, α = 0.05, two-tailed; *t* critical = ±1.99) to assess statistical differences in $PM_{2.5}$ and PM_{10} concentrations, the summarized results are in Table II.

The results indicate that $PM_{2.5}$ levels measured indoors were slightly lower than those recorded by CETESB, but this difference did not exceed the critical threshold and was therefore not statistically significant. Similarly, outdoor $PM_{2.5}$ concentrations were comparable to those reported by CETESB, with no significant differences observed. Furthermore, a direct comparison between indoor and outdoor $PM_{2.5}$ concentrations revealed no significant differences, suggesting that the levels in both environments were statistically similar, which can be explained because most of the indoor pollution in a classroom can be attributed to outdoor pollution that was brought inside by the students. Pearson correlation analysis showed moderate positive correlations for $PM_{2.5}$ between CETESB and UNESP Outdoor (r = 0.44) and between Indoor and Outdoor concentrations (r = 0.49), while the correlation between CETESB and Indoor was weaker (r = 0.29). This indicates that outdoor levels were more strongly associated with both CETESB measurements and indoor classroom concentrations, reinforcing the role of outdoor air as the main source of indoor $PM_{2.5}$ pollution.

In contrast, the analysis of PM_{10} concentrations revealed a more pronounced disparity. Indoor PM_{10} levels were significantly lower than those measured by CETESB. Likewise, outdoor PM_{10} concentrations were also significantly lower than CETESB's reported values, with very small *p*-values ($p < 0.001$), confirming that the differences were statistically significant. However, the comparison between indoor and outdoor PM_{10} levels showed no significant differences, indicating that the distribution of PM_{10} was similar in both environments. Pearson correlation analysis for PM_{10} showed weak or no correlation between CETESB and UNESP measurements ($r \approx 0$), but a moderate positive correlation was observed between Indoor and Outdoor levels (r = 0.48). This suggests that, while CETESB's PM_{10} dynamics were influenced by localized sources near the monitoring station, indoor and outdoor conditions at UNESP followed a more similar pattern.

These findings underscore a clear discrepancy in PM_{10} levels between the UNESP-Ibilce site and CETESB's monitoring station. The significantly higher PM_{10} levels reported by CETESB are likely attributable to its proximity to a major highway, which contributes to elevated emissions of PM in the 2.5–4 µm range.[34] This contrasts with the conditions at UNESP-Ibilce, where the absence of such localized sources of pollution results in significantly lower PM_{10} concentrations.

Table II. *t*-test (one-way factor) and Pearson test for PM from CETESB compared with annual indoor and outdoor PM measurements

Parameter	$PM_{2.5}$	PM_{10}
UNESP Indoor mean (μg m^{-3})	12.11	17.20
UNESP Outdoor mean (μg m^{-3})	13.77	19.22
CETESB mean (μg m^{-3})	14.34	34.22
t-Statistic CETESB-UNESP Indoor	-1.70	-6.69
t-Statistic CETESB-UNESP Outdoor	-0.51	-6.46
t-Statistic UNESP Outdoor-Indoor	-1.30	-1.38
Two-tailed *p*-value CETESB-UNESP Indoor	0.09	
Two-tailed *p*-value CETESB-UNESP Outdoor	0.61	
Two-tailed *p*-value UNESP Outdoor-Indoor	0.20	0.17
Pearson Test CETESB-UNESP Indoor	0.29	0.14
Pearson Test CETESB-UNESP Outdoor	0.44	-0.01
Pearson Test UNESP Outdoor-Indoor	0.49	0.48

All tests used a paired design with df = 72 (*t* Critical two-tail = ±1.99).

HYSPLIT of the dispersion on three different heights

HYSPLIT simulations were conducted on days with observed peaks in PM_{10} and/or $PM_{2.5}$ concentrations, as well as on days with minimal concentrations. Figures 8A through 8G capture the air masses that reached UNESP-Ibilce during peak moments at three different altitudes: 500 m, 1500 m, and 3000 m above sea level. All of these days were characterized by air masses passing through the states of Tocantins, Pará, Mato Grosso, Goiás, or a combination of these regions, where significant wildfires occurred (as shown in Figure 9). This allows us to infer those wildfires in central and northern Brazil led to a substantial increase in PM_{10} and $PM_{2.5}$ concentrations in the classrooms.

In Figure 8H, a PM peak was observed even in the absence of air masses from polluted areas, which can likely be attributed to local issues. During this period, leaf blowers were used in front of the classrooms. Conversely, in Figure 8I, from December 12, 2022, the peak of PM concentration was caused by classroom activities, in this case was the cleaning of an eraser inside the classroom.

Figures 8J through 8L illustrate the days with minimal particulate concentrations. No air masses passed through polluted or fire-affected areas during these times, and the classrooms had been cleaned in the preceding days.

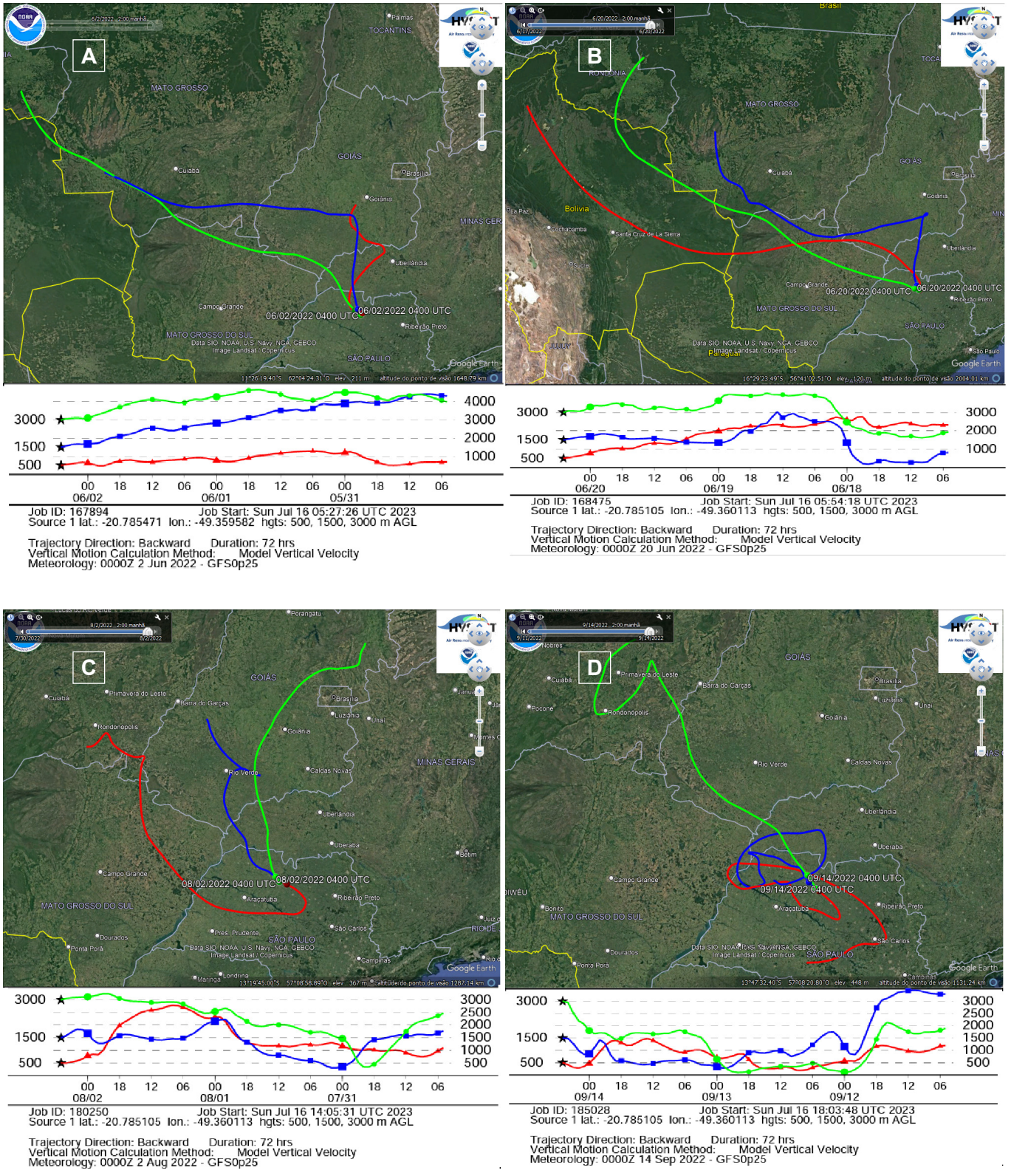


Figure 8. (A) Hysplit air dispersion on 2022-06-02 peak of PM_{10} and $PM_{2.5}$. (B) Hysplit air dispersion on 2022-06-20 peak of PM_{10} and $PM_{2.5}$. (C) Hysplit air dispersion on 2022-08-02 peak of PM_{10} and $PM_{2.5}$. (D) Hysplit air dispersion on 2022-09-14 peak of PM_{10} and $PM_{2.5}$. (continued on next page)

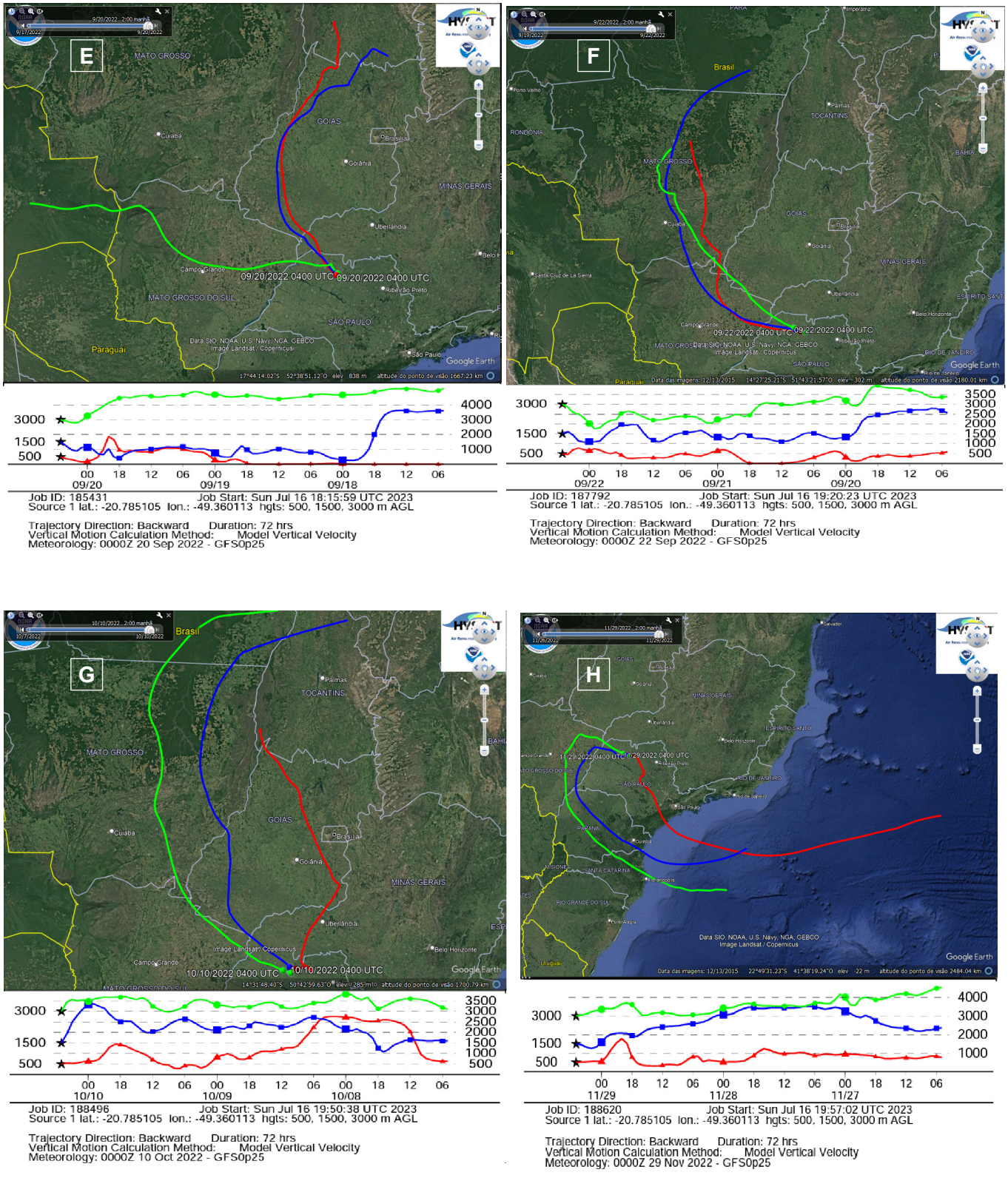


Figure 8 cont. (E) Hysplit air dispersion on 2022-09-20 peak of PM_{10} and $PM_{2.5}$. (F) Hysplit air dispersion on 2022-09-22 peak of PM_{10} and $PM_{2.5}$. (G) Hysplit air dispersion on 2022-10-10 peak of PM_{10} and $PM_{2.5}$. (H) Hysplit air dispersion on 2022-11-29 peak of PM_{10} and $PM_{2.5}$ indoors due to local factors. (continued on next page)

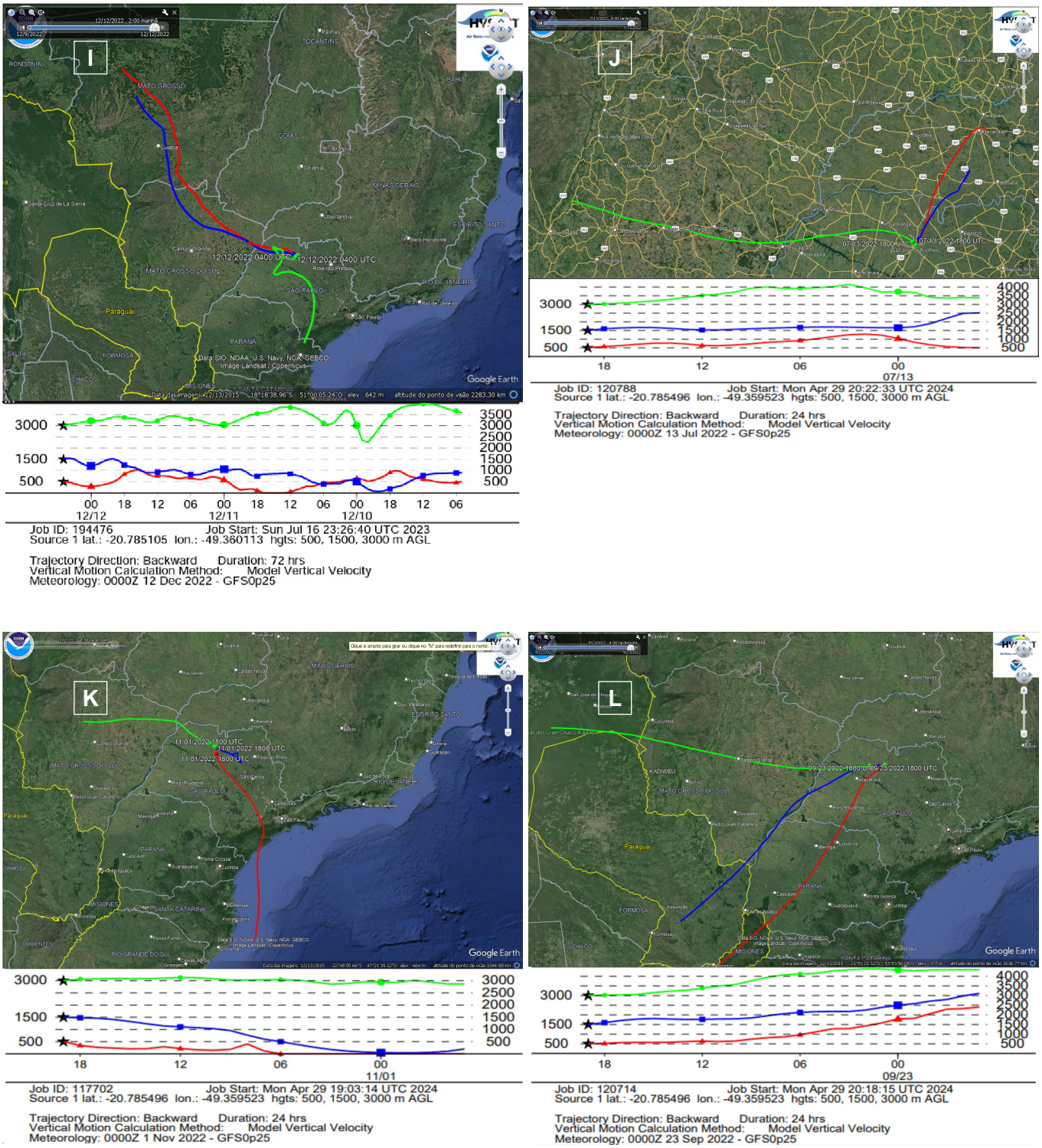


Figure 8 cont. (I) Hysplit air dispersion on 2022-12-12 peak of PM_{10} and $PM_{2.5}$ indoors due to local factors. (J) Hysplit air dispersion on2022-07-13 minimum of PM_{10} and $PM_{2.5}$. (K) Hysplit air dispersion on 2022-11-01 minimum of PM_{10} and $PM_{2.5}$. (L) Hysplit air dispersion on 2022-11-23 minimum of PM_{10} and $PM_{2.5}$.

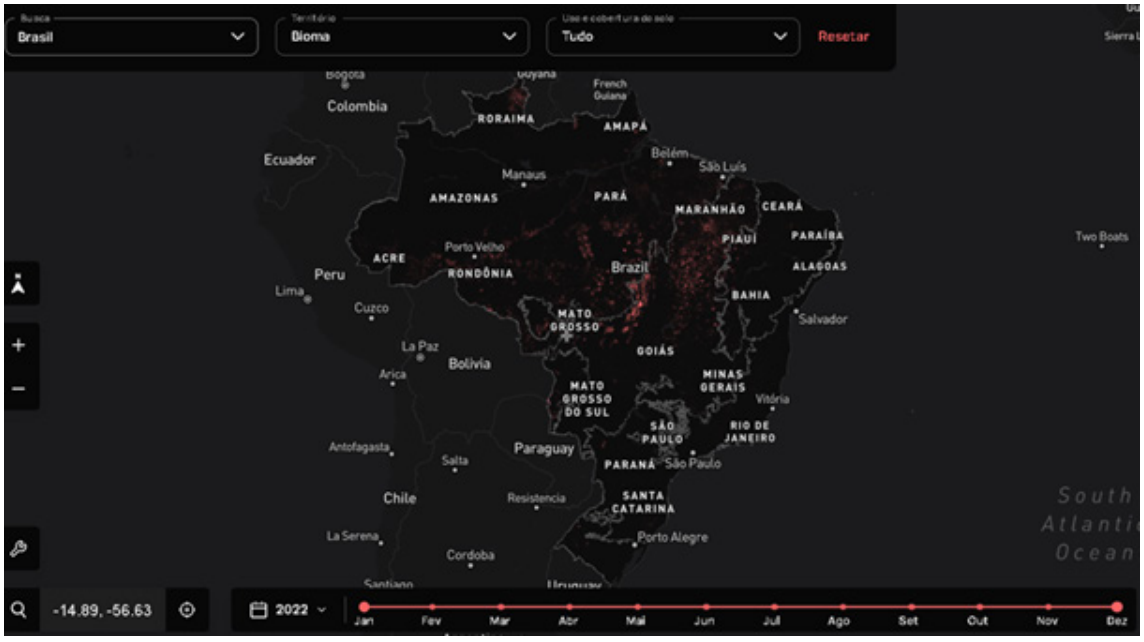


Figure 9. Map of Central Brazil with fire locations represented by dots from "Projeto MapBiomas – Coleção monitor do fogo" (2022).

All products, methods and tools of the MapBiomas Project are open access, transparent and publicly available in the internet (https://mapbiomas.org/) for non-commercial use.

Toxicological analysis

The health risk assessment indicated that the average daily dose (ADD) associated with a four-year exposure period only in the university environment is as in Table III when considering a mean $PM_{2.5}$ concentration of 12.5 μg m^{-3} and a PM_{10} concentration of 17.2 μg m^{-3} respectively.

Based on these values, the hazard quotient (HQ) was almost exceeding the reference threshold of 1 with only the 8 hours at the university. This finding suggests that continuous exposure to $PM_{2.5}$ at this level is when looking at the hole day could associate with potential non-carcinogenic health effects, such as respiratory and cardiovascular impairments, consistent with the health risk criteria established by the WHO and the EPA.

Regarding carcinogenic risk, the excess lifetime cancer risk (ELCR) calculated using PM_{10} literature SF value for both PM_{10} and $PM_{2.5}$ resulted in values of much lower than the commonly accepted risk range (10^{-6} to 10^{-4}), it is important to highlight that no specific slope factor for $PM_{2.5}$ has been established in official databases such as the EPA or WHO. Consequently, these results should be interpreted with caution, serving as an indicative rather than definitive estimate of carcinogenic risk.

Table III. Average daily dose for the exposed time for man and woman in the classroom

	ADD $PM_{2.5}$ $mg \times kg^{-1} \times day^{-1}$	ADD PM_{10} $mg \times kg^{-1} \times day^{-1}$	$HQ_{2.5}$	HQ_{10}	$ELCR_{2.5}$	$ELCR_{10}$
Male	0.0001730	0.0002353	0.593607	0.269102	3.46	4.71
Female	0.0001708	0.0002322	0.593607	0.269102	3.42	4.64

CONCLUSIONS

Upon evaluating the Figures 6 and 7 for the year 2022, it was evident that the presence of PM_{10}, both indoors and outdoors, consistently remained above the maximum value recommended by the WHO, 15 μg m^{-3}, throughout the monitoring period. These values generally aligned with the data monitored by the local CETESB station. This assessment is crucial for ensuring air quality in the indoor working environment of classrooms.

Moreover, for $PM_{2.5}$, which is significantly more harmful to human health and more resistant to physical deposition, the average value was found to be 12.5 ± 11.2 μg m^{-3} (12.5 ± 90% μg m^{-3}) inside the classrooms. This average is more than doble to the WHO's maximum recommended value of 5 μg m^{-3}. However, with a standard deviation of 90%, the levels often exceed the WHO guideline by almost 5 times the maximum, posing a potential health risk to students and faculty. Specifically, peak values for $PM_{2.5}$ were recorded at 43 μg m^{-3}, which is almost 900% higher than the WHO limit (5 μg m^{-3}). For outdoor areas, long sampling periods also revealed several intense peaks with values exceeding the WHO standard.

Therefore, even at average concentrations of 12.5 μg m^{-3} for $PM_{2.5}$ and 17.2 μg m^{-3} for PM_{10}, representative of typical university classroom conditions, prolonged exposure may pose significant health risks. The persistence of HQ values near 1 reinforces the necessity for mitigation strategies, including enhanced natural or mechanical ventilation, installation of air filtration systems, and institutional policies for continuous indoor air quality monitoring.

These findings underscore the importance of implementing policy measures, such as regular cleaning of classrooms between sessions and continual cleaning of curtains and air conditioning filters, to improve indoor air quality. This study did not monitor CO_2 levels, which can have a synergistic effect with particulates on cognitive performance in classrooms.

In conclusion, the presence of $PM_{2.5}$ and PM_{10}, both inside and outside the classroom environment, should be regarded as a significant concern. Students and faculty spend extended hours in classrooms and corridors, making air quality a critical factor for their health and well-being.

Conflicts of interest

The authors declare that they have no financial or management relationships that could be construed as a potential conflict of interest. No affiliations or funding sources, other than those explicitly acknowledged below, influenced the study design, data collection and analysis, interpretation of data, writing of the manuscript, or decision to publish.

Acknowledgements

This work was supported by "Agência UNESP de Inovação" (AUIN) – UNESP [02-2022].

REFERENCES

(1) Global Change Data Lab (England). *Our World in Data*. Number of deaths per year. 1 Jan 2025. Available at: https://ourworldindata.org/grapher/number-of-deaths-per-year (accessed July 7, 2025).

(2) World Health Organization. Ambient (outdoor) air pollution. WHO, 2022. Available at: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (accessed July 7, 2025).

(3) Alves, C. Aerossóis atmosféricos: Perspectiva histórica, fontes, processos químicos de formação e composição orgânica. *Quim. Nova* **2005**, *28* (5), 859–870. https://doi.org/10.1590/S0100-40422005000500025

(4) Querol, X.; Alastuey, A.; Viana, M.; Dall'Osto, M.; Moreno, T.; Gilardoni, S.; Pey, J.; Rodríguez, S.; Artíñano, B.; Sánchez de la Campa, A. Monitoring of PM_{10} and $PM_{2.5}$ around primary particulate anthropogenic emission sources. *Atmos. Environ.* **2001**, *35*, 845–858. https://doi.org/10.1016/S1352-2310(00)00387-3

(5) Wilson, R.; Spengler, J. D. *Particles in Our Air: Concentrations and Health Effects*. Harvard School of Public Health: Cambridge, MA, Harvard University Press, 1996.
(6) Gioda, A. Poluição Atmosférica e de Interiores: Influência Mútua e Seus Reflexos na Saúde. Doctoral thesis, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil, 2003.
(7) World Health Organization. Indoor air quality: biological contaminants. Rautavaara, 1998.
(8) Ormtstad, H.; Gaarder, P. I.; Johansen, B. V. Quantification and characterisation of suspended particulate matter in indoor air. *Sci. Total Environ.* **1997**, *193* (3), 185–196. https://doi.org/10.1016/S0048-9697(96)05337-5
(9) Sun, C. J.; Jia, H.; Zhao, J.; Zhang, W.; Duan, F.; Zhang, R. Study on size distribution of eight polycyclic aromatic hydrocarbons in airborne suspended particulates indoor and outdoor. *J. West China Univ. Med. Sci.* **1994**, *25* (4), 442–446.
(10) Vormittag, E. M. P. A.; Rodrigues, C. G.; de André, P. A.; Saldiva, P. H. N. Assessment and Valuation of Public Health Impacts from Gradual Biodiesel Implementation in the Transport Energy Matrix in Brazil. *Aerosol Air Qual. Res.* **2018**, *18*, 2375–2382. https://doi.org/10.4209/aaqr.2017.11.0449
(11) Pope, III, C. A.; Burnett, R. T.; Thurston, G. D.; Thun, M. J.; Calle, E. E.; Krewski, D.; Godleski, J. J. Cardiovascular mortality and longterm exposure to particulate air pollution: Epidemiological evidence of general pathophysiological pathways of disease. *Circulation* **2004**, *109*, 71–77. https://doi.org/10.1161/01.CIR.0000108927.80044.7F
(12) Miller, K. A.; Siscovick, D. S.; Sheppard, L.; Shepherd, K.; Sullivan, J. H.; Anderson, G. L.; Kaufman, J. D. Long-term exposure to air pollution and incidence of cardiovascular events in women. *N. Engl. J. Med.* **2007**, *356*, 447–458. https://doi.org/10.1056/NEJMoa054409
(13) Wang, J.; Li, R.; Li, G.; Meng, L.; Wu, D.; Wang, C.; Li, Z.; Yuan, Z.; Zhao, X.; Hou, Y. Urban particulate matter triggers lung inflammation via the ROS-MAPK-NF-κB signaling pathway. *J. Thorac. Dis.* **2017**, *9* (11), 4398–4412. https://doi.org/10.21037/jtd.2017.09.135
(14) Cançado, J. E. D.; Saldiva, P. H. N.; Pereira, L. A. A.; Lara, L. B. L. S.; Artaxo, P.; Martinelli, L. A.; Arbex, M. A.; Zanobetti, A.; Braga, A. L. F. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. *Environ. Health Perspect.* **2006**, *114* (5), 725–729.
(15) Hamra, G. B.; Guha, N.; Cohen, A.; Laden, F.; Raaschou-Nielsen, O.; Samet, J. M.; Vineis, P.; Forastiere, F.; Saldiva, P.; Yorifuji, T.; Loomis, D. Outdoor Particulate Matter Exposure and Lung Cancer: A Systematic Review and Meta-Analysis. *Environ. Health Perspect.* **2014**, *122* (9), 906–912.
(16) Bowe, B.; Xie, Y.; Li, T.; Yan, Y.; Xian, H.; Al-Aly, Z. The 2016 global and national burden of diabetes mellitus attributable to $PM_{2.5}$ air pollution. *Lancet Planet Health* **2018**, *2* (7), E301–E312.
(17) Riant, M.; Meirhaeghe, A.; Giovannelli, J.; Occelli, F.; Havet, A.; Cuny, D.; Amouyel, P.; Dauchet, L. Associations between long-term exposure to air pollution, glycosylated hemoglobin, fasting blood glucose and diabetes mellitus in northern France. *Environ. Int.* **2018**, *120*, 121–129. https://doi.org/10.1016/j.envint.2018.07.034
(18) Zhang, X.; Chen, X.; Zhang, X. The impact of exposure to air pollution on cognitive performance. *Proc. Natl. Acad. Sci. U.S.A.* **2019**, *115* (37), 9193–9197. https://doi.org/10.1073/pnas.1809474115
(19) Romero, M. T. B.; Dudzinska, M. R.; Torkmahalleh, M. A.; Barros, N.; Coggins, A. M.; Ruzgar, D. G.; Kildsgaard, I.; Naseri, M.; Rong, L.; Saffell, J.; et al. A review of critical residential buildings parameters and activities when investigating indoor air quality and pollutants. *Indoor Air* **2022**, *32* (11), e13144. https://doi.org/10.1111/ina.13144
(20) Cheng, Z.; Lei, N.; Bu, Z.; Sun, H.; Li, B.; Lin, B. Investigations of indoor air quality for office buildings in different climate zones of China by subjective survey and field measurement. *Build. Environ.* **2022**, *214*, 108899. https://doi.org/10.1016/j.buildenv.2022.108899
(21) Committee on Health Risks of Indoor Exposures to Fine Particulate Matter and Practical Mitigation Solutions. *Health Risks of Indoor Exposure to Fine Particulate Matter and Practical Mitigation Solutions*. National Academies Press, Washington, DC, 2024.

(22) Yuan, F.; Yao, R.; Yu, W.; Sadrizadeh, S.; Awbi, H.; Kumar, P. Dynamic characteristics of particulate matter resuspension due to human activities in indoor environments: A comprehensive review. *J. Build. Eng.* **2023**, *79*, 107914. https://doi.org/10.1016/j.jobe.2023.107914
(23) Stein, A. F.; Draxler, R. R; Rolph, G. D.; Stunder, B. J. B.; Cohen, M. D.; Ngan, F. NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bull. Amer. Meteor. Soc*. **2015**, *96*, 2059-2077, http://dx.doi.org/10.1175/BAMS-D-14-00110.1
(24) Draxler, R. R. HYSPLIT User's Guide. NOAA Tech. Memo. ERL ARL-230, NOAA Air Resources Laboratory, Silver Spring, MD, 1999.
(25) Draxler, R. R.; Hess, G. D. An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. *Aust. Met. Mag*. **1998**, *47*, 295-308.
(26) Draxler, R. R.; Hess, G. D. Description of the HYSPLIT_4 modeling system. NOAA Tech. Memo. ERL ARL-224, NOAA Air Resources Laboratory, Silver Spring, MD, 1997.
(27) U.S. Environmental Protection Agency. *Exposure Assessment Tools by Routes – Inhalation*. Available at: https://www.epa.gov/expobox/exposure-assessment-tools-routes-inhalation (accessed July 7, 2025).
(28) U.S. Environmental Protection Agency. *Exposure Factors Handbook, Chapter 6: Inhalation Rates*. Washington, DC, 2011. Available at: https://www.epa.gov/sites/default/files/2015-09/documents/efh-chapter06.pdf (accessed July 7, 2025).
(29) Centers for Disease Control and Prevention. National Center for Health Statistics. *Body Measurements*. Atlanta, GA. Last reviewed June 26, 2025. Available at: https://www.cdc.gov/nchs/fastats/body-measurements.htm (accessed July 7, 2025).
(30) Almamun, M.; Fallica, J.; Irwin, M.; Wier, E.; Wurcel, K.; Valerio Jr., L. G.; Yucesoy, B.; Rosenfeldt, H. Calculating Excess Lifetime Cancer Risk in ENDS Premarket Tobacco Product Applications; Division of Nonclinical Science, Center for Tobacco Products, U.S. Food and Drug Administration: Silver Spring, MD, June 3, 2024. Available at: https://www.fda.gov/media/180610/download (accessed July 7, 2025).
(31) Sekhavati, E.; Yengejeh, R. J. Particulate matter exposure in construction sites is associated with health effects in workers. *Frontiers in Public Health* **2023**, *11*. https://doi.org/10.3389/fpubh.2023.1130620
(32) Benson, R. W. Hazards of Food Contact Material: Phthalates. In: Motarjemi, Y. (Ed.). *Encyclopedia of Food Safety*. Academic Press: Amsterdam, Netherlands, 2014, Vol. 2, pp 438–443. https://doi.org/10.1016/B978-0-12-378612-8.00219-5
(33) U.S. Environmental Protection Agency. Reference concentration for chronic inhalation exposure (RfC). IRIS Summary. Integrated Risk Information System, 2007.
(34) Beji, A.; Deboudt, K.; Khardi, S.; Muresan, B.; Flament, P.; Fourmentin, M.; Lumière, L. Non-exhaust particle emissions under various driving conditions: Implications for sustainable mobility. *Transportation Research Part D: Transport and Environment* **2020**, *81*, 102290. https://doi.org/10.1016/j.trd.2020.102290